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UNIVERSITY OF ALBERTA

The Geology, Ore Textures and Metal Grades of the S-65 and K-77 Ore Bodies, Pine Point, Northwest Territories.

BY

(C) Jan Herman Schutze

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE

OF Master of Science

Department of Geology

EDMONTON, ALBERTA

Fall 1991

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DEGREE FOR WHICH THESIS WAS PRESENTED: Master of Science

YEAR THIS DEGREE WAS GRANTED: 1991

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Jan Herman Schutze

Box 7, Site 2, RR# 4,

Stony Plain, Alberta, Canada

T0E 2G0

Date ..May 13.....1991

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The undersigned hereby certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled: The Geology, Ore Textures and Metal Grades of the S-65 and K-77 Ore Bodies, Pine Point, Northwest Territories, submitted by Jan Herman Schutze in partial fulfillment of the requirements for a degree of Master of Science.

R. St J. Lambert
.....
Prof. R. St J. Lambert (Supervisor)

.....
Prof. R.E. Folinsbee

.....
Prof. R.D. Morton

.....
Prof. L.R. Plitt

Date ....., 1991

ABSTRACT

The S-65 and K-77 ore bodies of the Pine Point Mississippi Valley type deposits were studied in order to provide a relationship between ore textures and ore grades.

Both prismatic ore bodies were mapped according to four textural units. Each unit has certain assemblages of textures of which typical ones can be used as a quick identifier: The breccia zone with massive colloform sphalerite; the zone of intense recrystallization with coarse crystalline, star shaped sphalerite; the zone of internal sediments with aggregates of large, euhedral galena; marcasite rich zones with massive or disseminated marcasite. Recrystallization is the by far dominating texture forming process during which crystal aggregates are "cleaned". This cleansing process has continuously since the Givetian to the present released hydrocarbons which facilitate the continuous precipitation of sulfides.

The metal distribution maps support the theory of ore forming solutions travelling through lateral extensions or wings. Lead with a poor mobility contours the initial location of precipitation out of solution. Zinc contour lines show secondary movements and lateral extensions. Marcasite shows late solution activity.

The superimposure of metal contour maps over texture maps yielded consistent values within the ore bodies. However, such values are only applicable to ore grade predictions once they have been established for one ore

body. The values vary greatly from one to the other ore body within the mining district.

The above study supports that active ore forming solutions precipitated sulphides continuously since the Givetian. It appears that the initial precipitation of sulfides occurred at a faster rate. After that initial stage the solutions continued to enter and exit through the lateral channels bringing new metals, removing existing sulfides and redistributing sulfides.

ACKNOWLEDGEMENTS

The writer is indebted to numerous persons for providing opportunity, assistance, support and patience in the execution of this thesis.

Thanks goes to the staff of the Geology Department of Pine Point Mines Ltd. for sharing their knowledge and information.

Thanks goes to Pine Point Mines Ltd. for sample shipping and provision of an exciting employment in the Department of Grade Control.

During my studies I have benefitted greatly from advice and discussions with Dr. R.St.J.Lambert and Dr. R.D.Morton. Their assistance was invaluable as was the critical review of this thesis. I am greatly indebted.

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1. INTRODUCTION

1.1. History

The history of the Pine Point ore deposits reaches back to approximately the year 1890 when prospectors on their way to the Yukon discovered oxidized sulfides. Some minor prospecting and staking took place between the initial discovery and 1928.

In 1929 the Northern Lead and Zinc Company was formed as a joint venture of the Boston Syndicate, Atlas, Ventures Limited and the Consolidated Mining and Smelting Company Limited. The exploration work resulted in no discoveries of economic importance and almost all interest in the properties was lost by 1940.

In 1947 the Consolidated Mining and Smelting Company Limited with Ventures Limited and later with the Northern Lead and Zinc Company, acquired exclusive prospecting rights for a 500 square mile concession area. An eight year exploration project, consisting of widespread drilling lead to the discovery of mineralized bodies that had no surface expressions.

In 1951 Pine Point Mines Limited was formed with Cominco Limited holding 51%. Production at Pine Point started in 1964 after the construction of a railroad line to Edmonton (N. Campbell, 1966). The total production of Pine Point Mines Limited between 1964 and 1983 was 58.2 million

short tons averaging 3.0% Pb and 6.6% Zn. The published reserves at the end of 1983 were 25.7 million tons with 2.7% Pb and 6.3% Zn (Rhodes et al., 1984).

In the following years, lower lead and zinc prices, higher stripping ratios and increased dewatering costs negatively affected Pine Point Mines Ltd.'s operations. In 1986 production was boosted to maximize the cash flow, while mining only the most economic ore reserves (15.8 million tons). Excess concentrate was stockpiled for processing at the smelter in Trail, B.C., in future years. In 1986 the exploration program was temporarily suspended due to poor lead and zinc prices.

In October, 1986, a consortium of companies led by Teck Corp. purchased a 31% interest in Cominco Ltd. Subsequently, this consortium was involved in the decision making on Pine Point Mines Ltd.

The detailed plans of a shutdown of Pine Point Mines Ltd.'s operations were released in early 1987. Mining stopped in mid-1987 and milling continued into early 1988. In April, 1988, Pine Point Mines Ltd. purchased a 33% interest in the Polaris Mine on Little Cornwallis Island in the N.W.T. (The Northern Miner, 1983 to 1988).

1.2 Statement of Objectives of this Study

The production group in the Geology Department of Pine Point Mines was involved in ore reserve calculations from diamond drill holes, ore grade predictions from blast drill holes, daily pit mapping and visual ore grade estimates and the grade control of ore stock piles.

The employment of the author in the production group of Pine Point Mines Limited offered a great exposure to the various ore bodies while being mined. The continuous exposure to the ore bodies had lead the staff of the Geology Department of Pine Point Mines Ltd. to the hypothesis that the sulfide concentrations were closely related to their textures and to paleokarst features. This thesis represents the study of these relationships within the S-65 and K-77 ore bodies to substantiate this hypothesis. This correlation of visible textures with ore grades is unique in itself as well in its scale, as the entire ore bodies were examined in great detail during their excavation. The ore bodies were mapped on pitscale on a daily basis, handspecimen textures were described and classified, the origins of the handspecimen textures were researched by microscope studies. These groups of textures were then correlated with detailed grade distribution maps to yield the relationship which has not before been used to aid grade control nor has this relationship been published before.

It is the aim of this thesis to study these

relationships on the pit scale, not on a regional scale.

The recognition of such relationships can improve the efficiency and accuracy of any future grade control and render valuable information for the understanding of the genesis and paragenesis of these particular Mississippi Valley Type deposits.

1.3 Summary of the Thesis

It was the object of this thesis to study the relationships between grade contours and ore textures of the S-65 and K-77 ore bodies to aid grade control procedures and to shed more light on the genesis of the Pine Point deposits.

Between 1964 and 1983 the Pine Point deposits produced 58.2 million short tons of ore averaging 3.0% lead and 6.6% zinc. In 1988 all concentrate production was terminated.

The southwest trending, Givetian Pine Point Barrier Complex separates the MacKenzie Basin from the Elkpoint Basin. Karstification of the barrier in the Pine Point area occurred on the North, Main and South Trends.

The S-65 ore body of the Pine Point ore deposits produced 634,000 tons of combined ore with lead and zinc grades of 1.2% and 5.7% respectively.

The prismatic mineralized breccia occurred in H and I-Facies limestones and dolomites of the Sulfur Point Formation and had its base in the Muskeg Formation.

The mapping of ore textures lead to the identification of five ore zones which are:

The breccia zones,

The zones of intense recrystallization,

The marcasite-rich zones,

The peripheral zones,
The detrital ore zones including
the Pleistocene Sinkhole.

Each zone is characterized by typical ore textures which were categorized in this thesis.

Stoping at the location of crossing solution channels along the South Trend resulted in the opening of a cave, which was filled with H and I-limestone fragments breaking off the ceiling. The cave was closed at the top and had its base in the J-facies. Initial mineralization was the formation of a breccia matrix consisting of sphalerite and galena growing out of solution. Multiple stages of ore remobilization occurred subsequently which overprinted previously formed ore textures. Remobilizing processes were dissolution, recrystallization, mechanical and chemical redeposition of ore. These processes have obscured textural zones and the recognition of ore-forming stages is difficult.

Sphalerite occurs in a great variety of textures and is wider spread, which indicates that it is more affected by redistributing processes.

Galena textures are of less varieties and confined to smaller areas. Lead is less mobile and after crystallization as galena mainly affected by recrystallization. This observation is of importance,

because the plotting of the Pb% distribution provided an outline of the initial ore deposition.

A channel of intense recrystallization cuts through the breccia body. This channel must have remained open long after the initial emplacement of the ore, as it has entirely overprinted preexisting textures.

Marcasite appears to be very mobile and can be associated with a number of late stages of solution activity. Marcasite occurs in disseminated or massive aggregates. Late stage sphalerite crystals have been found to replace marcasite.

To present the metal and metal ratio distribution in the S-65 deposit, the values from blast-hole analyses were plotted and contoured.

On the first bench five ore zones can be identified. On the third bench the ore zones are reduced to one central ore zone.

At the west side of the ore body is a highly visible lateral extension on all three mining levels. Less visible and split up are the lateral channels at the north and east of the ore body.

On all three benches of S-65, the sinkhole coincides with a S-lateral extension and a S-ore zone. The theory that the ore of the sink hole is mechanically derived from immediate surroundings is supported by the Pb/Zn ratio of 1/5 which is characteristic for the S-65 ore body.

Lead outlines the early sulfide deposition which is also approximately the outline of the breccia zone. The observed distribution of lead reflects low mobility.

The sphalerite distribution displays a great variety in all ranges of Zn% grades which corresponds with a great variety in sphalerite textures. The cause for this is the greater mobility of sphalerite. The Zn% contours show very clearly the lateral extensions.

The Fe distribution is the result of late, overprinting processes. A Fe rim visible on the first bench is related to the Pleistocene sinkhole. The W and S-lateral extensions have, especially on the second bench, noticeably increased Fe% values.

There seems to be a inverse relationship between galena and marcasite.

For the purpose of a correlation the (Pb%+Zn%)/Fe% distribution maps and the textural zonation map were superimposed. The resulting averages for the textural zones were as follows:

Two Breccia Zones:

Total grade average: 3.20 (Pb%+Zn%)/Fe%

Zone of Intense Recrystallization:

Total grade average: 3.02 (Pb%+Zn%)/Fe%

Marcasite Zones:

Total grade average: 0.80 (Pb%+Zn%)/Fe%

The (Pb%+Zn%)/Fe% grades of the central zones, i.e. the Breccia, Intense Recrystallization and Disseminated Marcasite Zones, is constant between 3.0% to 3.2%. This indicates that the processes of recrystallization and iron enrichment in these zones did not change the average ore grades. However, the high grade ore zone in the Breccia Zone is larger and more pronounced than that of the latter zones which suggests that the processes of recrystallization and iron enrichment evened out the grades by degrading high grade and upgrading low grade ore. While disseminated marcasite is the result of gradual replacement and recrystallization, the massive marcasite appears to have filled open cavities after the removal of pre-existing host and ore. This explains the low averages of the (Pb%+Zn%)/Fe% ratio in the massive marcasite zones.

K-77 is a prismatic ore body in the west part of the Main Trend. Proven reserves of the K-77 deposit were 647,700 tons at 3.9 % combined Pb+Zn. In the process of ore texture mapping of the first bench of K-77 and the ore texture logging of drill core four texture zones were identified. There are a few typical ore textures which allow a quick identification of the ore zone.

The peripheral zone is readily identified by the boxwork texture. Late marcasite often accumulates along fractures and is followed by occasional sphalerite. Groups of euhedral galena crystals characterize the internal

sediment zone. Sphalerite occurs in patches of disseminated crystals. In the zone of intense recrystallization blue-grey and white sparite are a common host. Very common are coarse crystalline galena dendrites and sphalerite stars. In the main ore zone the amount of repeated cross-cutting textural relationships makes it impossible to assign certain textures to certain stages of mineralization. Stages can only be followed on a local scale of meters, beyond which they are again overprinted. The sulfides occur in the following settings:

- Rimming and cementing breccia fragments
- Filling large primary or secondary open spaces
- Associated with recrystallization
- Associated with internal sedimentation

The ore texture and host rock mapping shows that the ore zone widens to the north and south with depth. A lateral, tabular karst channel, mineralized by colloform sphalerite and some disseminated galena and sphalerite crystals, extends beyond the southern boundary of the cross section.

The presence of lateral karst extensions, the dome like closing in of unaltered limestone at the top and the unaltered limestone at the bottom of the deposit suggest that the mineralizing solutions entered the breccia zone

from the sides. The galena concentration at the present top of the deposit suggest that water entering from the top was involved in the process of ore precipitation.

The Pb%+Zn% distribution map delineates the general trends within the ore body. It reveals an east - west elongation with lateral extensions on the east and west sides of the central high grade zone. It appears that the main flow direction of sulfide precipitating solutions was from the west to the east. There is an indication for a lateral extension to the north, however, it is overprinted by a Pleistocene sinkhole. Internal sediments separate the northern part of the high grade ore from the southern portion.

The Pb% distribution is as in the S-65 ore body more confined to the core of the central high grade zone and shows the northern lateral extension less clearly. Because lead is less mobile it shows the outline of primary ore deposition.

The greater mobility of zinc subjects sphalerite more than galena to the processes of redistribution by solutions after primary deposition.

The lead + zinc over iron ratio map provides a combination of the previously described maps.

The areas of 0.5 to 1.0 (Pb%+Zn%)/Fe% typically fall into the Peripheral Zone representing a marcasite rim around the central ore zones. The higher than 5.0

(Pb%+Zn%)/Fe% are concentrated in the Breccia or Main Ore Zone.

The ore texture zones were superimposed on the (Pb%+Zn%)/Fe% distribution map, yielding typical ore grades for the individual ore texture zones. The resulting average grades within the individual texture zones were as follows:

Peripheral Zone

Total grade average: 2.44 (Pb%+Zn%)/Fe%

Zone of Intense Recrystallization

Total grade average: 3.4 (Pb%+Zn%)/Fe%

Zone of Internal Sediments

Total grade average: 4.6 (Pb%+Zn%)/Fe%

Breccia Zone:

Total grade average: 6.4 (Pb%+Zn%)/Fe%

The average (Pb%+Zn%)/Fe% values for the individual zone increase gradually from the outside to the center of the ore body. The lowest values are in the Peripheral Zone where lead/zinc mineralization is rare and marcasite occurs frequently in fractures and cavities. The highest values of the combined ore over iron ratio occur in the central, brecciated ore zone. The zones of recrystallization and internal sedimentation occur at the approximate same distance and orientation to the central zone. However their respective combined ore over iron ratios

differ substantially. This difference is caused by the following processes: In the zone of recrystallization, with an average ratio of 3.4, there was no redistribution of galena, sphalerite or marcasite with the exception of minor, small scale mobilization associated with the recrystallization. This has kept the ore grades constant since the initial formation of the ore deposit. In the Zone of Internal Sedimentation, with an average (Pb%+Zn%)/Fe% ratio of 4.6, material was initially removed to create caves. These caves were subsequently infilled with internal sediments which were in the case of the K-77 deposit derived from the high grade breccia zone.

2. GENERAL GEOLOGY, STRATIGRAPHY AND GEOLOGY OF THE ORES OF THE PINE POINT AREA

2.1 The General and Geological Setting

In the Great Slave Lake region and in northwestern Alberta, the Pre-Cambrian Shield is unconformably overlain by Ordovician and Devonian sediments. These sediments form a part of the continental, Interior Platform. This platform has its northwestern boundary at the erosional edge which forms a southwest trending line through Yellowknife, the Taltson River and the Slave River (Fig.2.1.I). The Paleozoic sediments dip gently towards the west.

At the location of the Pine Point Mines property the southwest trending Pine Point Barrier Complex separates the MacKenzie Basin to the north and west from the Elkpoint Basin to the south and east. In the MacKenzie Basin mainly shale and shaley carbonates were deposited. The sedimentary rocks of the Elkpoint Basin consist of carbonate and anhydrite behind the barrier, and of halite and anhydrite further to the southwest (Fig. 2.1.I).

The gentle dip (1.9 m/km) of the Paleozoic strata causes a subcropping of the Givetian barrier complex in the Pine Point region, approximately 100 km west of the erosional edge. To the west and at greater depth the carbonate complex can be traced into British Columbia. At Rainbow-Zama, 160 km southwest of Pine Point, and at other

locations in that vicinity, oil reservoirs occur within the Barrier Complex. Karstification of the barrier in the Pine Point area occurred on three linear trends of maximum solution. These trends are parallel to the 65° azimuth strike of the barrier and are referred to as the North, Main and South Trends.

Today, the area south of Great Slave Lake has virtually no relief and swamps and small ponds occur in a Pleistocene and Holocene overburden. When flying over the mining district, circular sink holes are noticeable and indicative of recent collapse of karst structures in the underlying carbonates.

Basement lineaments shown on Figure 2.1.I are part of the Athapuscow Aulacogen or related to the McDonald Fault System. These basement lineaments have frequently been said to have been related to the formation of the barrier complex. It was pointed out by Rhodes et al. (1984) that the trends of the lineaments from the East Arm of Great Slave Lake are slightly divergent from the barrier trend. Also, the karsted and mineralized strata occur in structures that formed at least in the late stages of barrier sedimentation. These structures developed without major faulting under temperature and salinity conditions and at a depth favorable for a high activity of barrier-forming organisms.

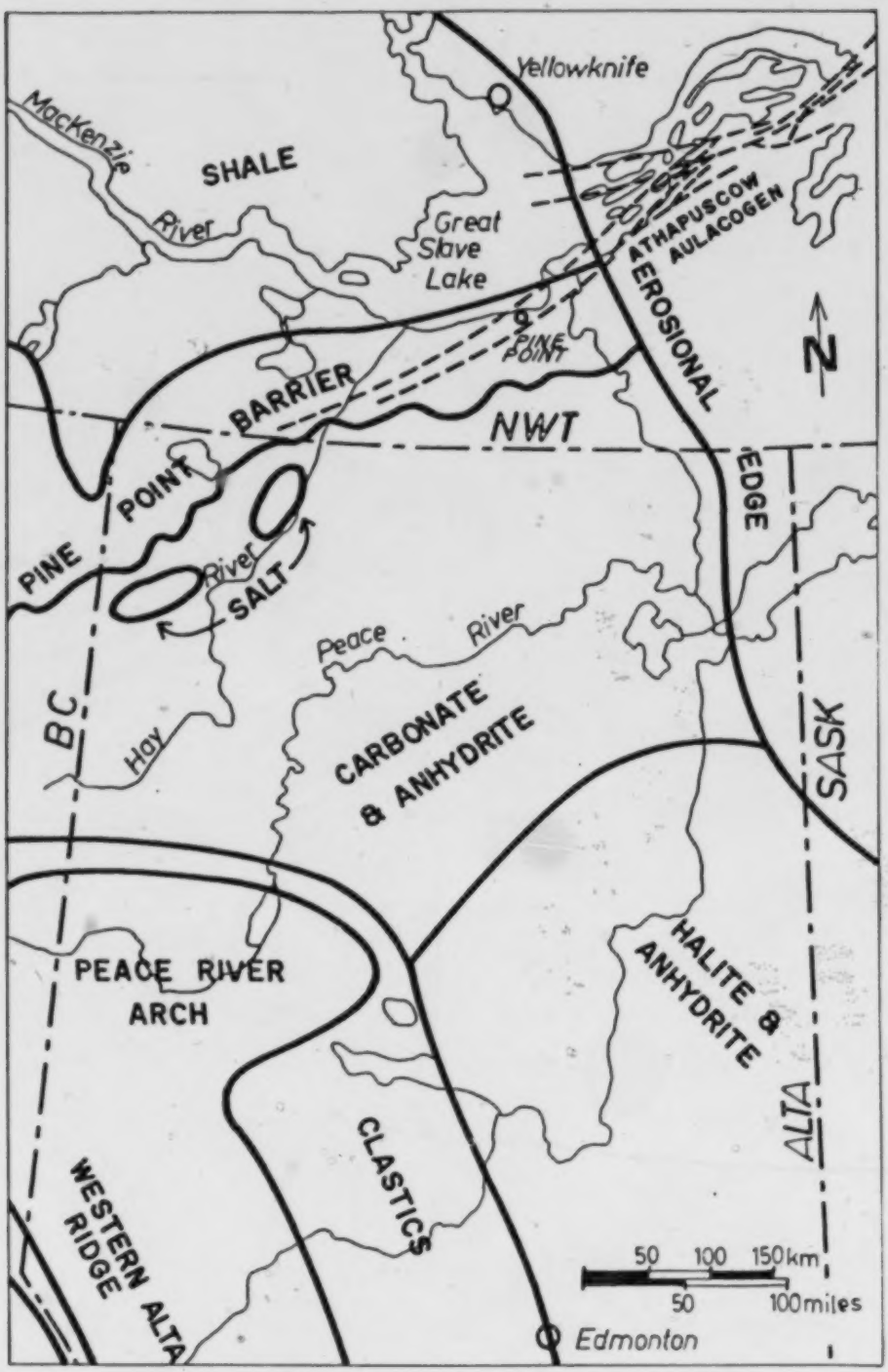


Figure 2.1.I Location and general geology of the Pine Point Barrier.

2.2 Stratigraphy

The Pine Point deposits are hosted by a Givetian sequence. The Keg River Formation forms the underlying carbonate platform. The Lower Pine Point Formation and the Sulphur Point Formation make up the lower and upper parts of the barrier reef. The Muskeg Formation represents the back reef deposits in the Elkpoint Evaporite Basin south of the reef. North of the barrier reef, the Buffalo River Formation and the Windy Point Formation represent the fore reef deposits. Overlying the fore reef, reef and back reef deposits are the Watt Mountain Formation and Slave Point Formation (Rhodes et al., 1984).

The barrier reef was formed by repeated regressions and transgressions. The Pine Point Formation and the Lower Sulphur Point Formation represent the active growth of the lower part of the barrier during the Lower- to Mid-Givetian. A regression exposed the barrier introducing coarse dolomitization referred to as Presqui'lization. The Upper Sulphur Point Formation is the result of a transgression with new reef growth. This period was followed during Upper Sulphur Point time by another regression associated with dolomitization. Gradual transgression began during the late Upper Sulphur Point time, however, inundation of the reef did not occur until Watt Mountain time (Lantos, 1983).

The formations in the Pine Point area were broken down into members and facies, the discussion of which is beyond the scope of this study. Detailed studies of the facies were performed by Skall (1975), Lantos (1983) and Rhodes (1984). Some of the facies relevant to the S-65 and K-77 ore bodies are described in the respective introductory chapters. The stratigraphic sequence is shown on Figure 2.2.I. The subcropping of the formations and some facies is shown on Figure 2.2.II.

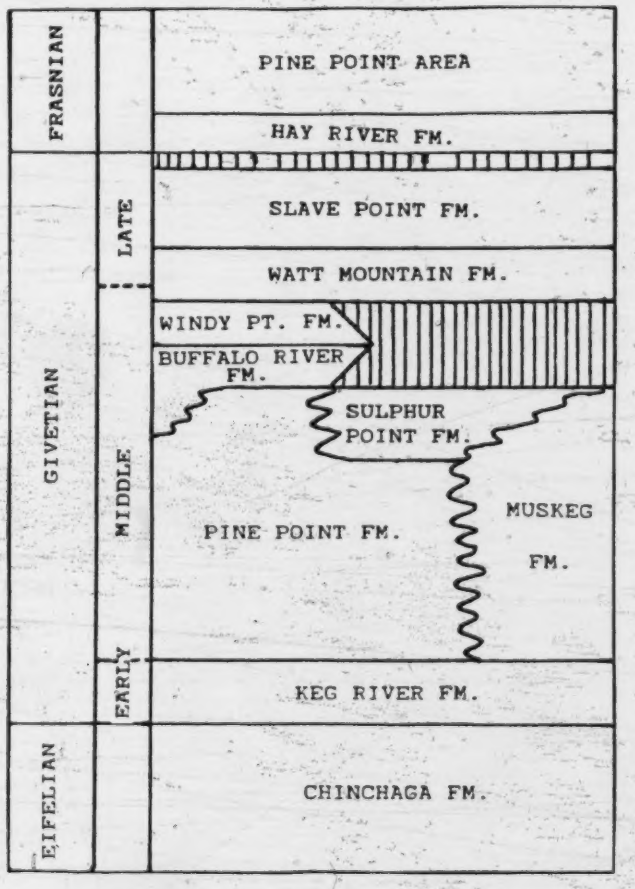


Figure 2.2.I Stratigraphic Sequence Diagram.
(Adapted from Rhodes et al., 1984)

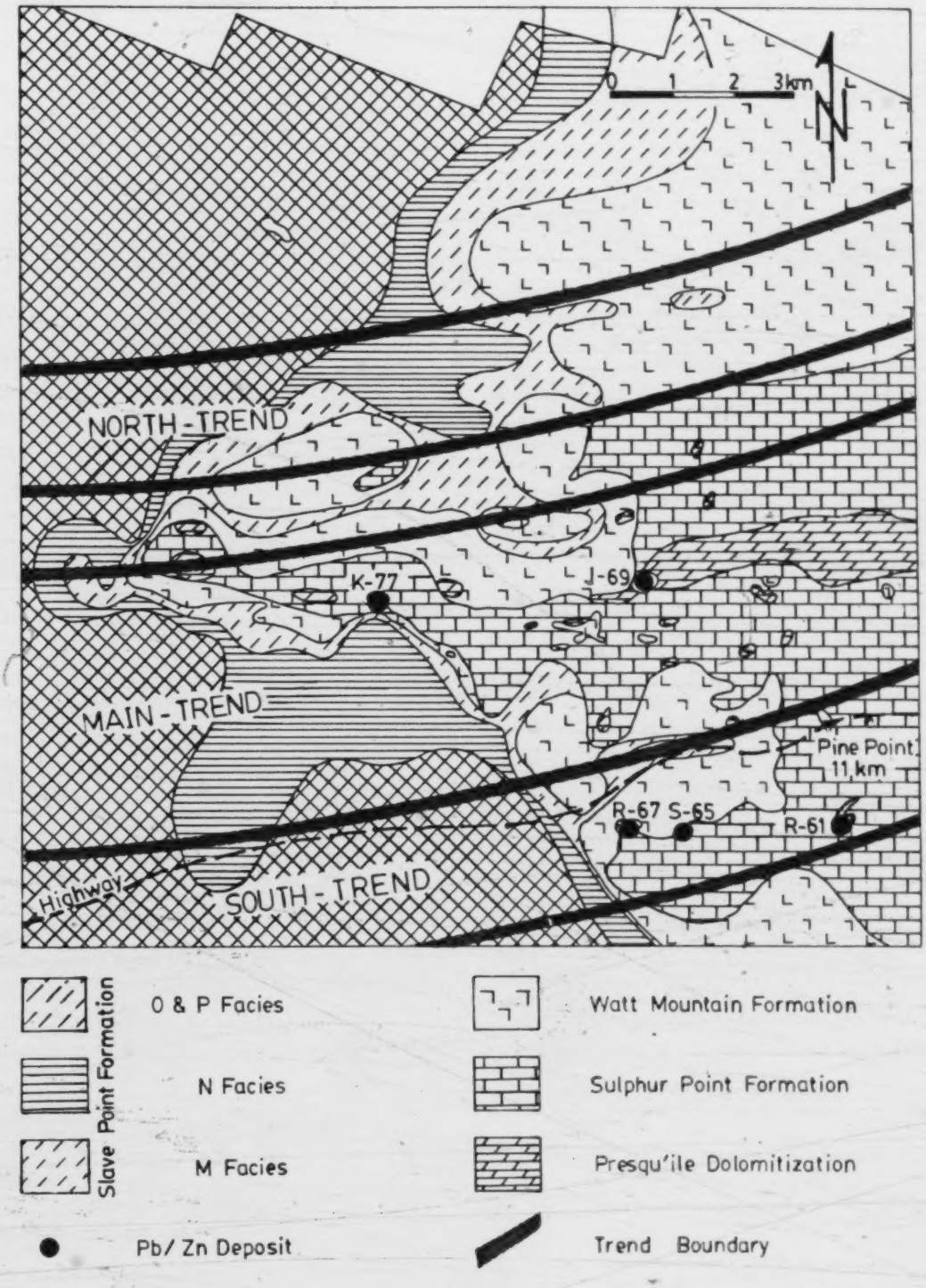


Figure 2.2.II Subcrop geology of the S-65 and K-77 area.

(Adapted from Rhodes et al., 1984)

2.3 General Economic Geology

Lead Statistics

During 1988, at the time of the closure of Pine Point Mines, the lead production from mines (lead recycling not included) of the Western World was 2,338,000 tonnes; Canada ranked third in the Western World's lead production from mines with 368,000 tonnes, behind the U.S with 420,000 tonnes and Australia with 478,000 tonnes. The U.S. replaced Canada as the second largest producer as a result of increased production in the U.S. and a 40,000 tonnes reduction in Canadian production caused by the closure of Pine Point Mines. This trend continued through 1989 and 1990 with new mines starting in the U.S. The total lead production of the Western World in 1988 was 4,302,000 tonnes (4,410,000 tonnes in 1989). 47.2% of the Western World's total metal production was produced from recycled materials. This percentage of recycled lead has further increased in the last two years. The average U.S. producer price in 1988 was 37.1 cent/lb. The lead price has not significantly changed in 1989 (39.3 c/lb) and 1990 (38.0 c/lb). The pattern of lead use has in recent years been marked by a growing market share for batteries (over 60%) and a decline for lead additives in petroleum (less than 3%). Other uses are: pigments, paint compounds, glass and glazes (13%), rolled and extruded products (8%), cable sheathing (5%), alloys (4%) and ammunition (2%).

Zinc Statistics

In 1988, at the time of the closing of Pine Point Mines, the zinc production from mines (zinc recycling not included) of the Western World was 5,106,000 tonnes; Canada was the world's leading producer with 1,348,000 tonnes, followed by Australia with 739,000 tonnes. In 1988/9, Canada used the stockpiles from Pine Point to offset falling mine production (1,216,000 tonnes in 1989). The average U.S. producer price at the time of the Pine Point closure was 41.92 cent/lb. This price increased in 1990 to 70 cent/lb. Zinc is the most important non-ferrous metal in tonnage behind aluminum and copper. Zinc is used mainly in coatings (over 40%). Other uses are rolled zinc, batteries, zinc oxide and other chemicals.

The Lead / Zinc Mining Industry

The closing of the mine at Pine Point in 1987 required increased production from stockpiles. This was the most important factor behind the 1987 increased lead / zinc mine production of Canada. The 1988 Canadian mine production of lead and zinc fell due to the milling of ore at the mine in April, 1988. There are ore stockpiles remaining on the property. In 1989 and 1990 Canadian lead/zinc production fell further due to technical and other difficulties at other mines. Pine Point Mines Limited is producing at the Polaris Mine in the N.W.T.

The Gay's River Mine (N.S.) just opened, Nanasivik in the N.W.T. is producing.

The Faro Mine of Curragh Resources Inc. in the Yukon produced 180,000 t/y of zinc and 110,000 t/y lead in 1987. Production fell in 1988 and 1989 due to strikes. The Grum, Vangorda and Cirque deposits are being developed for production in the 1990's.

The Hudson Bay Mining and Smelting Co. Ltd. produces from the Ruttan Mine, Callinan Zn/Cu deposit and Chisel Lake Mine. The Ruttan Mine in Manitoba produces 15,000 t/y of zinc.

Noranda Inc. produces 50,000 t/y of zinc in Winston Lake, Ontario. The Isle Dieu Deposit in Quebec produces 50,000 t/y of zinc.

East West Minerals NL opened in November 1989 the Caribou Mine in New Brunswick producing 125,000 t/y of lead/zinc concentrate. Daniels Harbour (N.F.L.) is shut down.

The most important world development is the opening of Cominco's Red Dog Zinc - Lead Mine in Alaska. It is the second largest mine of this type ever, behind Broken Hill Mines (Australia). The reserves at the Red Dog Mine are 85 million tons at 17.1% zinc, 5.0% lead and 2.4 oz/ton silver. The deposit occurs in black shales, cherts and limestones of Mississippian age.

2.4 The Geology and Classification of the Ores

The geological study of ores from carbonate-hosted lead zinc ore deposits, including the Pine Point ore bodies, has been performed since their first discoveries. An understanding of the ore genesis and distribution obviously contributes to any mining performance. The study of ore textures, of each deposit in Pine Point has in the past been part of other related studies and has been approached from many directions. The nomenclature and classification of ore textures frequently originates from:

- Carbonate-host textures
- Genetic terminology
- Geochemistry of crystal growth
- Geometric or descriptive aspects

An additional problem for textural studies is the scale on which to classify. Crystals and textures have their origin in minute nuclei which may result in macroscopic textures on a 100 meter scale.

Rhodes et al.,1984, described three main sulfide settings in the breccia zones of the prismatic ore bodies in Pine Point: Replacement of internal sediments in the collapse breccia, open space fillings between breccia fragments and impregnation and replacement of breccia fragments. The karst networks between prismatic ore bodies may contain solution channel-way ore, bedding replacement

ore or peripheral ore. The terminology chosen by Rhodes et al. for macroscopic textures is mostly genetic.

Schwartz, 1951, presented a genetic classification of microscopic ore textures according to primary, secondary, exsolution and structural aspects.

Sass-Gustkiewicz, 1975, used macroscopic textures to identify stages of mineralization in the Cracow-Silesian deposits of Poland. The textures basically fall into two classes: Syngenetic and epigenetic. Syngenetic textures include disseminated mineralization simultaneous with karsting. Epigenetic textures include cavity fillings, metasomatic replacement, disaggregation, sedimentation and leaching.

Kyle, 1978, studied the controls of lead-zinc mineralization at Pine Point and related ore textures to changing solutions during ore-forming stages of the deposits.

Anderson, 1975, also described textures as a result of changing solution activities. The most important sphalerite and marcasite texture is the colloform texture caused by rapid precipitation from a supersaturated solution. Skeletal, hopper and dendritic galena are reported as a result of rapid crystal growth and directional supply of nutrients.

Amstutz and Park, 1967, classified diagenetic, microscopic textures of carbonate-hosted lead-zinc deposits.

Typical textures of this category include recrystallization, dissolution, grain growth, grain orientation, pressure twinning, fracturing and residual accumulation. These diagenetic processes are frequently observed along stylolytic seams.

Amstutz and Bubenicek, 1967, introduced a geometric classification of micro- and macroscopic rock textures, free of genetic connotations. The triangular diagram for texture classification has the following end-members at its corners: top: linear textures; left bottom: network textures; right bottom: disseminated textures.

Smith, 1964, made observations on crystal growth of isolated and aggregated crystals. His studies include mono-mineralic and poly-mineralic aggregates. He derives a theoretical, textural classification using increasing complexities of crystal aggregates.

In this thesis the ore textures were mainly classified by association with typical textural zones. The ore textural zones identified in the S-65 and K-77 ore bodies are:

a) The breccia ore zones
b) Zones of recrystallized ore, including
   - Peripheral ore zones
   - Internal recrystallized ore zones

c) Detrital ore zones, including

- Internal ore sediments
- Modern sinkholes

d) Iron-rich ore zones

The nomenclature of the ore zones involves genetic connotations. The terminology applied in this thesis is commonly used by the geologists of Pine Point Mines including Rhodes et al., 1984.

The individual textures within each zone were described using a variety of the above cited methods.

THE S-65 ORE BODY

3.1 Location and History

The S-65 ore body occurs 10 km west of the town of Pine Point, N.W.T. (Fig.2.2.II). Other ore bodies mined in the vicinity include T-58, R-61 and R-67. The S-65 ore body was mined out between 1979 and 1980, producing 634,000 tons of ore with grades of approximately 1.2% Pb and 5.7% Zn. Detailed geological pit mapping of the host rock and the mapping of ore textures for this thesis began when mining had advanced to the third bench of the pit.

3.2 The General Geology of the S-65 Ore Body

The Subcrop Geology

The S-65 ore body, and the above mentioned neighboring deposits, occur within a domal feature (Rhodes et al.,1984) in the Sulfur Point Formation (Fig.2.2.II). This high forms an island in the overlying Watt Mountain and Slave Point Formation. The Muskeg Formation, which underlies the Sulfur Point Formation, increases in thickness from north to south, which can be accounted for by ongoing subsidence in the southern region of the mining area throughout the time of deposition of the Pine Point Formation and Muskeg Formation. While subsidence occurred in the south, the barrier region of the north remained stable. However, a tectonic uplift of

the Pine Point Barrier cannot be entirely discounted as the cause of the varying thickness.

The R-67, S-65, R-61, T-58 and, further away, the W-17 and X-16 ore bodies occur in a line paralleling the Pine Point Barrier (65° azimuth) and form what is referred to as the South Trend. The ore bodies along this trend are considered unusual, because they do not align as well as the ore bodies along the Main and North Trends. Also, no tabular, connecting karst features were found by drilling between the ore bodies. However, marcasite-rich collapses west of R-61 are indicative of a connecting karst network and, therefore, support the existence of a South Trend. The ore bodies along this trend have their roots in the J-facies at the base of the Presqu'ile development (Rhodes et al.,1984).

Stratigraphy

The S-65 deposit is a prismatic ore body and mineralization occurs in a paleokarst collapse breccia. The collapse zone is hosted by H and I-facies limestones of the Sulfur Point Formation. These facies are assemblages of bioclastic grainstones and rudstones of back reef lagoonal to supratidal environments (Lantos, 1983).

The base of this collapse zone in this karst system is formed of rocks of the J-facies of the Muskeg Formation.

The J-facies of the Muskeg Formation was deposited in restricted, shallow water conditions. It is a variable sequence of thinly bedded carbonates and evaporates indicating alternating subtidal and supratidal depositional environments. To the south the J-facies interfingers with anhydrite and gypsum beds of the Muskeg Formation (Lantos, 1983).

The H and I-facies in the vicinity of the S-65 ore body are approximately 30 m-thick and are covered by Pleistocene overburden and by modern bogs. Part of the H and I-facies, the Watt Mountain Formation and the Slave Point Formation, were eroded before and during the Pleistocene.

3.3 Karsting and Host Rock Mapping on Pit Scale

Prior to ore deposition, karsting developed a major cave with numerous cavities and lateral extensions, which were infilled by detritus from brecciation, crackle brecciation, internal sedimentation, and by recrystallization. The latest event was the forming of a Pleistocene sinkhole. At some localities repeated karsting and infilling have caused multiple overprinting of previously formed textures. Rhodes et al. (1984) concluded from their studies that initial karsting took place during the late Mid-Givetian in period(s) of subaerial exposure preceding the deposition of the Watt Mountain, Buffalo River and Windy Point Formations.

The S-65 breccia zone has an approximate depth of 30 m from the erosional surface of the H and I-carbonates to the top of the J-facies which forms the base of the mined out portion of the breccia zone. The breccia zone could possibly continue downward through parts of the J-facies in which case the unaltered J-facies found at the bottom of the mined part of the collapse zone represents just non-recrystallized and unmineralized zones within a still continuing breccia zone. However, no holes were drilled deep enough to support this hypothetical possibility.

In map view the collapse zone is oval in shape, with a length of approximately 100 m and a width of 65 m. The long axis has an orientation of 10° azimuth. In three dimensions the breccia body is upright cylindrical and not cone shaped, as are some other ore bodies in the mining district (Fig.3.3.III).

Brecciation

The breccia fragments filling the collapse zone generally coarsen upward. The breccia fragments consist of dolomitized H and I-facies limestones. Watt Mountain Formation limestone, green clay, fine clastic dolomite, and argillaceous and bituminous insoluble residue (Bachelor, 1980). Also present are fragments of internal sediments, mineralized fragments and pieces of massive marcasite. The latter are indicative of rebrecciation of earlier cave fill.

Large blocks of presqu'ilized H and I or J-facies occurring at the top and bottom of the breccia zone could have been bottom highs or roof pendants in the paleocave. (The terms Presqu'ile and presqu'ilized dolomite refer to coarse recrystallization typical for dolomites of the Pine Point area and were first introduced by Norris (1965).)

On the first bench brecciation conforms to the general oval shape of the ore body without any irregularities in its outline. In the NE-quadrant of the oval brecciated zone, an island of presqu'ilized, but unbrecciated H and I-facies limestone and dolomite occurs. This island probably represents a roof pendant in the paleocave because its size is considerably larger than any of the breccia fragments in the vicinity and it was not observed on the lower second and third benches of the pit (Fig.3.3.IV A, B and C).

On the second bench the lower part of the northern pit wall shows a lateral extension of brecciation beyond the limits of the pit. The width of the extension is approximately 16 m and the trend is 10° azimuth. In the pit wall of the third bench this same channel shifts to the east to approximately 30°. The cross-section (Fig.3.3.V) shows the shape of this brecciated lateral extension. This feature does not occur on the first and upper part of the second bench.

On the second and third bench an outward bulge towards the W (approximately 290° azimuth) of the ovoid brecciated zone is observed. The brecciation did not extend into the pit walls on the second bench. Due to the funnelshape of the pit the brecciated zone does, however, extend into the pit walls of the third bench.

In the southern end of the brecciated zone of this pit any evidence of channel like extensions has been overprinted by the Pleistocene sinkhole.

Internal Sediments

Internal sediments are very abundant along the periphery of and within the breccia zone, drastically increasing towards the bottom of the paleocave. These internal sediments are light to dark grey, commonly fine to medium grained and are composed of fragments of carbonates of uncertain origin, probably Sulfur Point and Slave Point Formations. Green colored fragments of the Watt Mountain Formation have been identified within the internal sediments.

The marcasite content of the internal sediments increases towards the top of the breccia body. An increase in marcasite was also observed in the NW-portion of the second bench and the third bench.

Rebrecciation of internal sediments is very common. Broken up clasts of such rebrecciated internal

sediments can occur in re-embedded coarse grained internal sediments (Fig.3.3.I). The coarse internal sediments were recrystallized, mineralized, fractured and fracture-filled in later stages of solution activity. It is often difficult to differentiate between brecciated fragments of previously formed internal sediments and breccia fragments of overlying formations. Careful pit mapping allowed the comparison of recrystallized fragments with unaltered internal sediments and the recognition of rebrecciated and recrystallized internal sediments.

Figure 3.3.I. Internal sedimentation on the third bench of S-65. Recrystallization has overprinted the original textures and has introduced sphalerite stars.

Recrystallization

A halo of recrystallized H and I-facies limestone 15 to 50 m wide surrounds the central collapse zone. Recrystallization of two different types occurs within this halo:

- Fine crystalline dolomitization produces a sucrosic texture with crystal sizes ranging from 0.1 to 1.0 mm. Original, fine details have been destroyed, but gross morphologies have been preserved.
- Coarse dolomitization, (presqu'ilization) results in dolomite rhombs of 1 to 5 mm size. All original detail has been destroyed. Dunsmore (1975) observed that in the halo the Presqu'ile dolomite occurs in the following settings:
  - lining irregularly shaped vugs
  - as component of "striped zebra" rocks
  - as dolomite pseudo breccia
  - as partitions of a boxwork that encloses voids that range in size from mm to m across.

These, by Dunsmore described textures, are the result of replacement of original limestone by ingrowing dolomite. In the case of a boxwork texture the dolomite is ingrowing from fractures (Fig.3.3.II).

Recrystallization is also associated with lateral solution activity: Of the rock types in the vicinity of the

ore body, the Presqu'ile dolomites have the highest porosity and present the most favourable environment for the flow of mobile solutions. The locations of solution entry and/or exit should therefore be marked by increased presqu'ilization which has the effect of increasing porosity. Solution channels entering from the top or the bottom of the paleocave or collapse zone cannot be recognized in plan view, but lateral solution activity and associated presqu'ilization can be recognized on the geologic maps of the mined benches.

On the first bench presqu'ilization extends beyond the pit walls at three locations. These lateral extensions occur at 10°, 30° and 290° azimuth measured around the centre of the above described generally oval shaped ore body. Flat lying, pseudobrecciated lenses of presqu'ilized dolomite occur at these locations along the pit walls (Fig.3.3.V).

Due to the funnel shape of the pit, the pit walls of the second and third benches expose Presqu'ile dolomite all around. Only on the SE-side of the second bench are unaltered H and I-Facies limestones exposed. The other walls consist of presqu'ilized dolomite. A breccia channel to the north and the Pleistocene sinkhole in the south are also recognized on the second bench. The excavation of the third bench is too narrow for the identification of lateral cave extensions. This bench occurs completely within breccia and presqu'ilized dolomite.

Figure 3.3.II. Pseudo brecciation and boxwork textures are the result of advancing recrystallization.

Crackle Brecciation

At the transition from Presqu'ile dolomite to the central collapse zone the dolomite occurs as a crackly breccia (Bachelor, 1980). Boxwork, zebra and pseudo-brecciated dolomite is broken into blocks of varying size which have been cemented by Presqu'ile dolomite or by sulfide mineralization at these locations.

The Pleistocene Sinkhole and Modern Karsting

In the southern portion of the pit the ancient collapse zone has been disturbed by modern karst activity. A Pleistocene sinkhole extends up to 35 m into the ore body on the second bench and less on the first and third benches. The material which fills this sinkhole consists of Pleistocene till mixed with fragments of the Watt Mountain Formation, i.e. silty clay and varved clay. The till often comprises granite boulders which can be up to 50 cm in diameter.

Portions of the clastic sulfides which have been deposited in the Pleistocene sinkhole represented economic mineralization. The textures and grades of these Pleistocene ores are discussed in later chapters of this thesis. Unaltered H and I-facies limestones as well as mineralized or unmineralized Presqu'ile dolomite drape and slump towards the sinkhole from all sides.

In the vicinity of the sinkhole, the breccia

material of the ancient collapse shows evidence of Pleistocene channelling: The channels range from centimeters to meters in diameter and are filled with internal sediments of the same composition as the Pleistocene sinkhole.

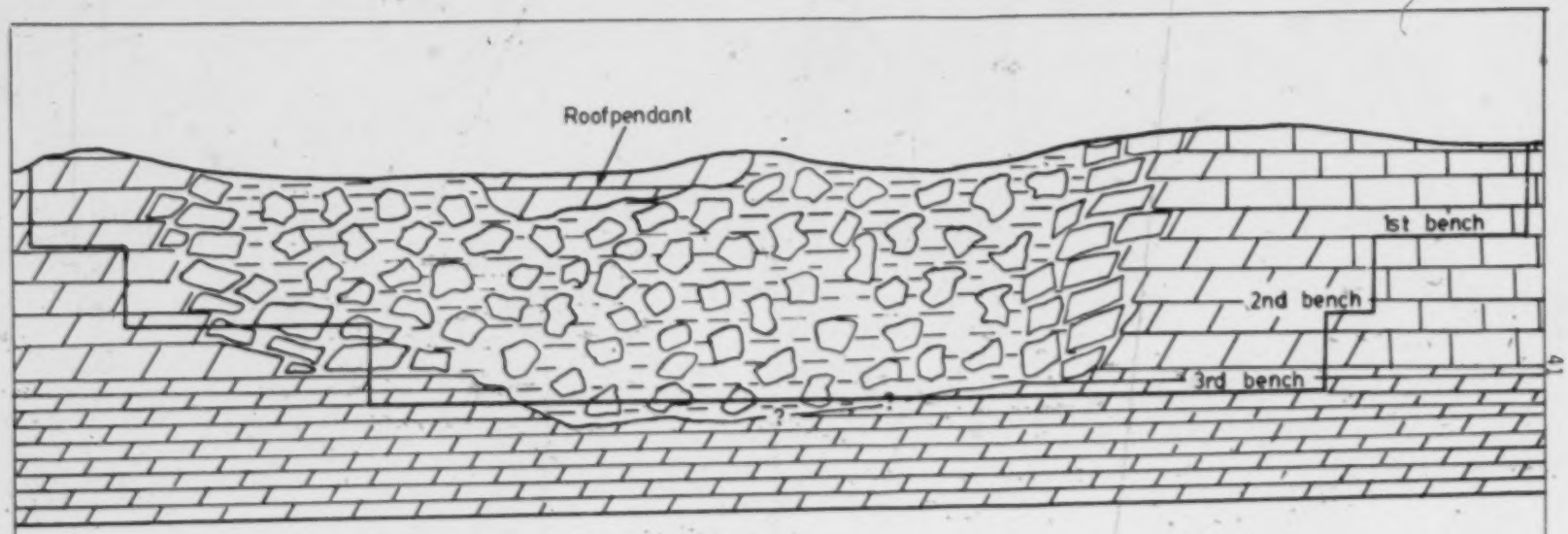
There is also evidence for karst activity related to the present surface of the carbonates. Numerous stylolytic layers occur in the limestones peripheral to the ore body, which occasionally widen to karst channels 2 to 5 m wide and 0.5 to 1 m thick. These channels are filled with light green clay material.

These features support the interpretation that overprinting of the Devonian and younger karst textures occurred during Pleistocene and Recent times.

Conclusions from the Mapping of Karst Features and Host Rock

The prismatic mineralized breccia occurred in H and I-Facies limestones of the Sulfur Point Formation and had its base in the Muskeg Formation. A roof pendant indicates that the paleo cave was closed at the top. Lateral extensions at different levels point towards a tabular channel system of the South Trend. The author mapped the different pit levels of the ore body using the nomenclature and units recognized by T. Bachelor (1980). These units were: The H and I-limestone, dolomitized H and I-limestones, collapse breccia with internal sediments, and a Pleistocene sink hole. The composition of the internal sediments which

occur around and within the collapse breccia and the composition of the Pleistocene sink hole indicate mechanical and chemical redistribution of the ore from Mid-Givetian to Pleistocene time.



Unaltered H&I facies limestone

Crackle breccia

Dolomitized H&I facies limestone

Breccia and Internal sediments

Dolomitized J-facies limestone

0 100ft 200ft

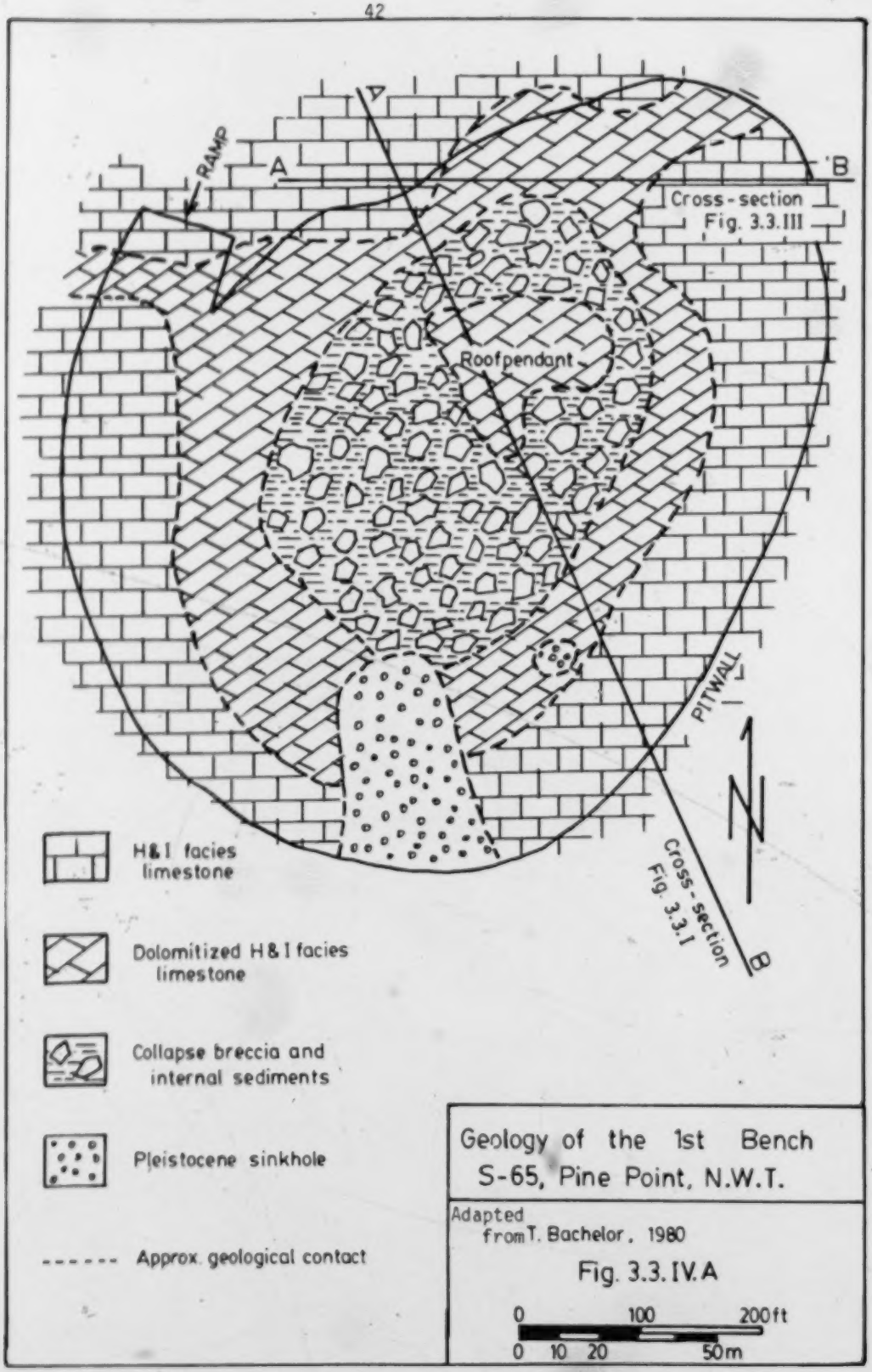
0 10 20 50m

Geological Cross-section, 15° NW
S-65, Pine Point, N.W.T

Adapted from T. Bachelor, 1980

Fig. 3.3. III

see Fig. 3.3.IIA for location of section

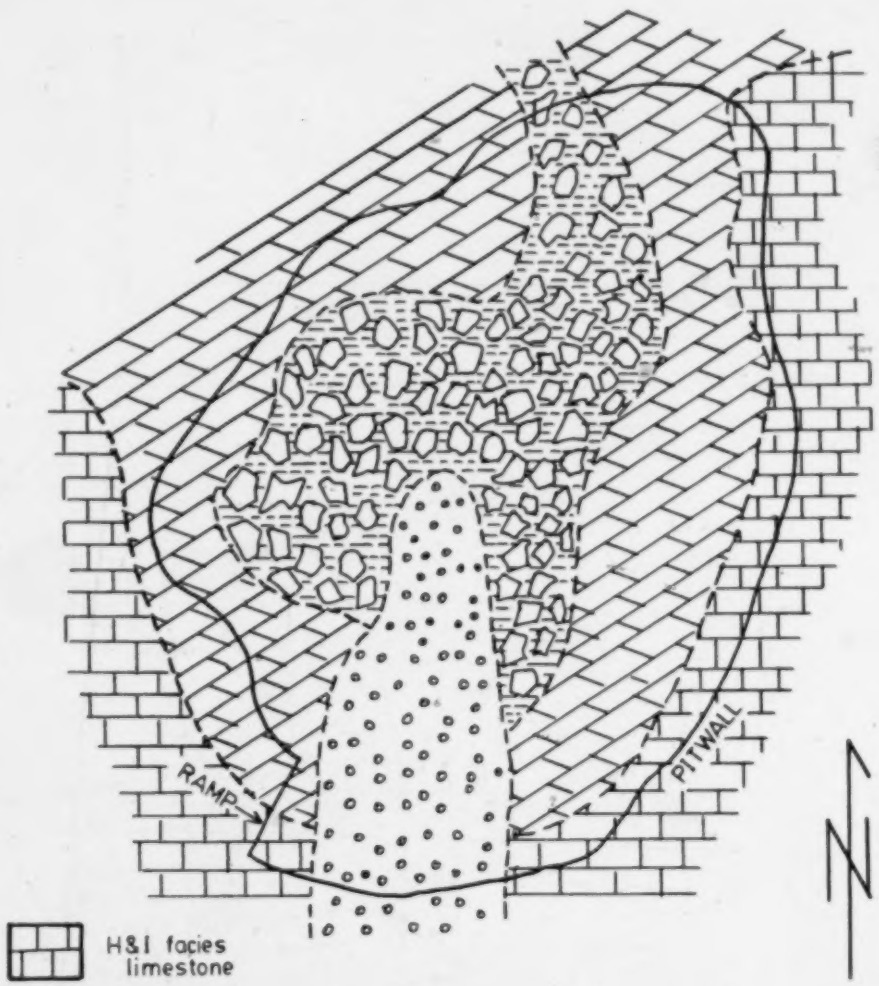


Geology of the 1st Bench
S-65, Pine Point, N.W.T.

Adapted
from T. Bachelor, 1980

Fig. 3.3.IV.A

0 100 200ft
0 10 20 50m



H&I facies limestone

Dolomitized H&I facies limestone

Collapse breccia and internal sediments

Pleistocene sinkhole

---- Approx. geological contact

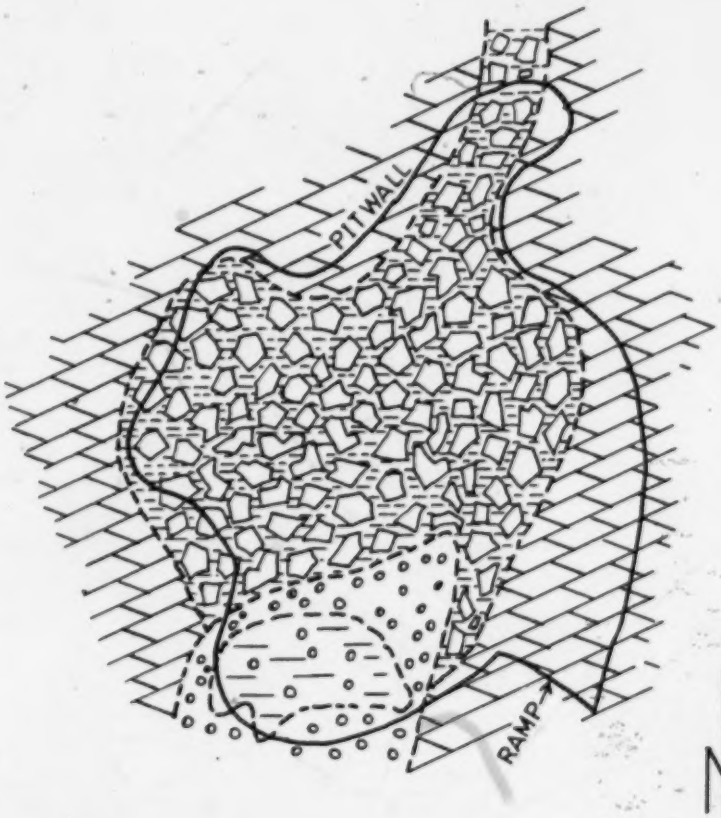
Geology of the 2nd Bench S-65, Pine Point, N.W.T.

Adapted from: T. Bachelor, 1980

Fig. 3.3.IV.B

0 100 200 ft

0 10 20 50m



Dolomitized H&I facies limestone

Collapse breccia and internal sediments

Pleistocene Sinkhole

Ore grade (>2%Pb+Zn) mineralization in Pleistocene sinkhole

---- Approx. geological contact

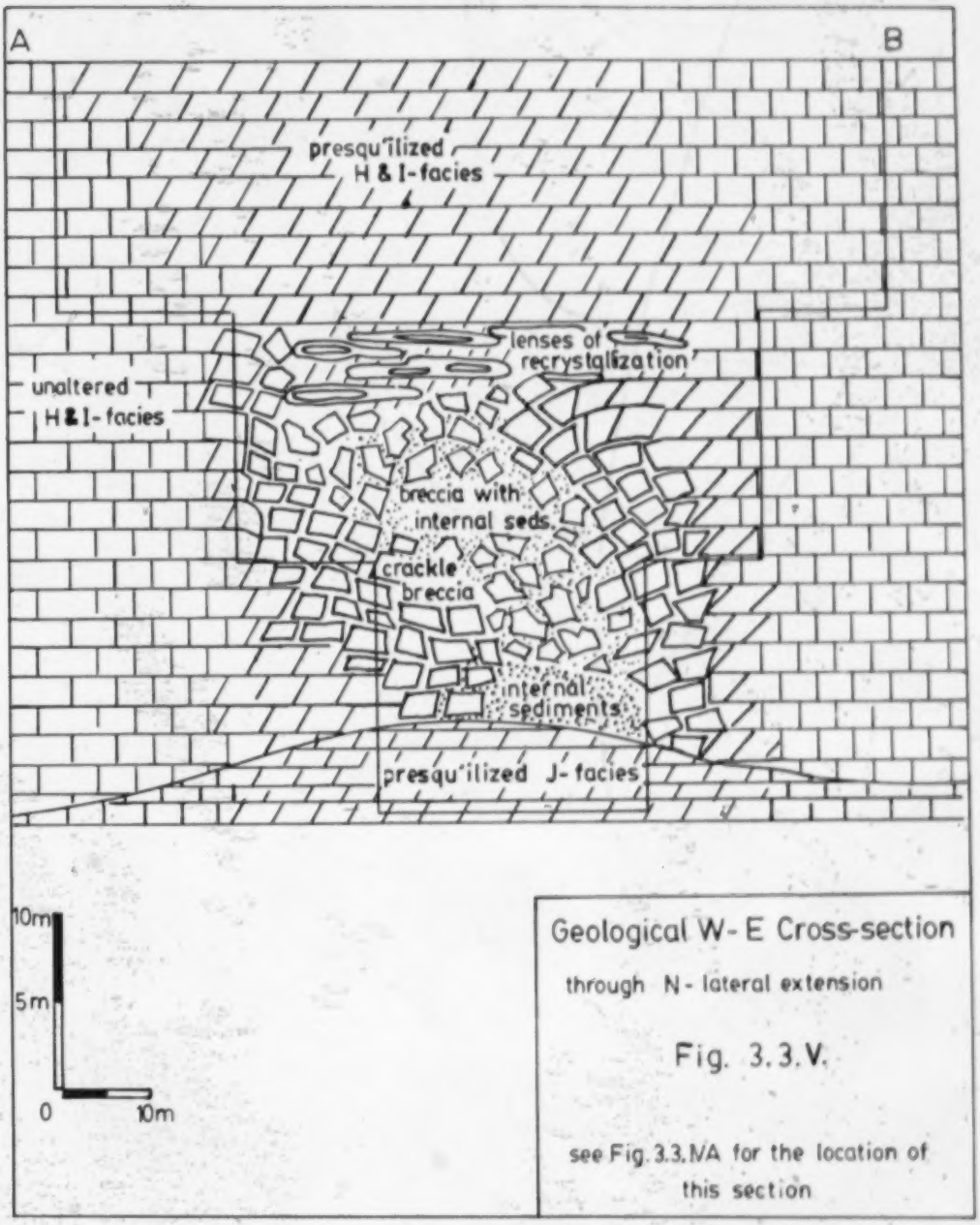
Geology of the 3rd Bench S-65, Pine Point, N.W.T.

Adapted from: T. Bachelor, 1980

Fig. 3.3.N.C

0 100 200 ft

0 10 50m



Geological W-E Cross-section

through N-lateral extension

Fig. 3.3.V.

see Fig. 3.3.IVA for the location of this section

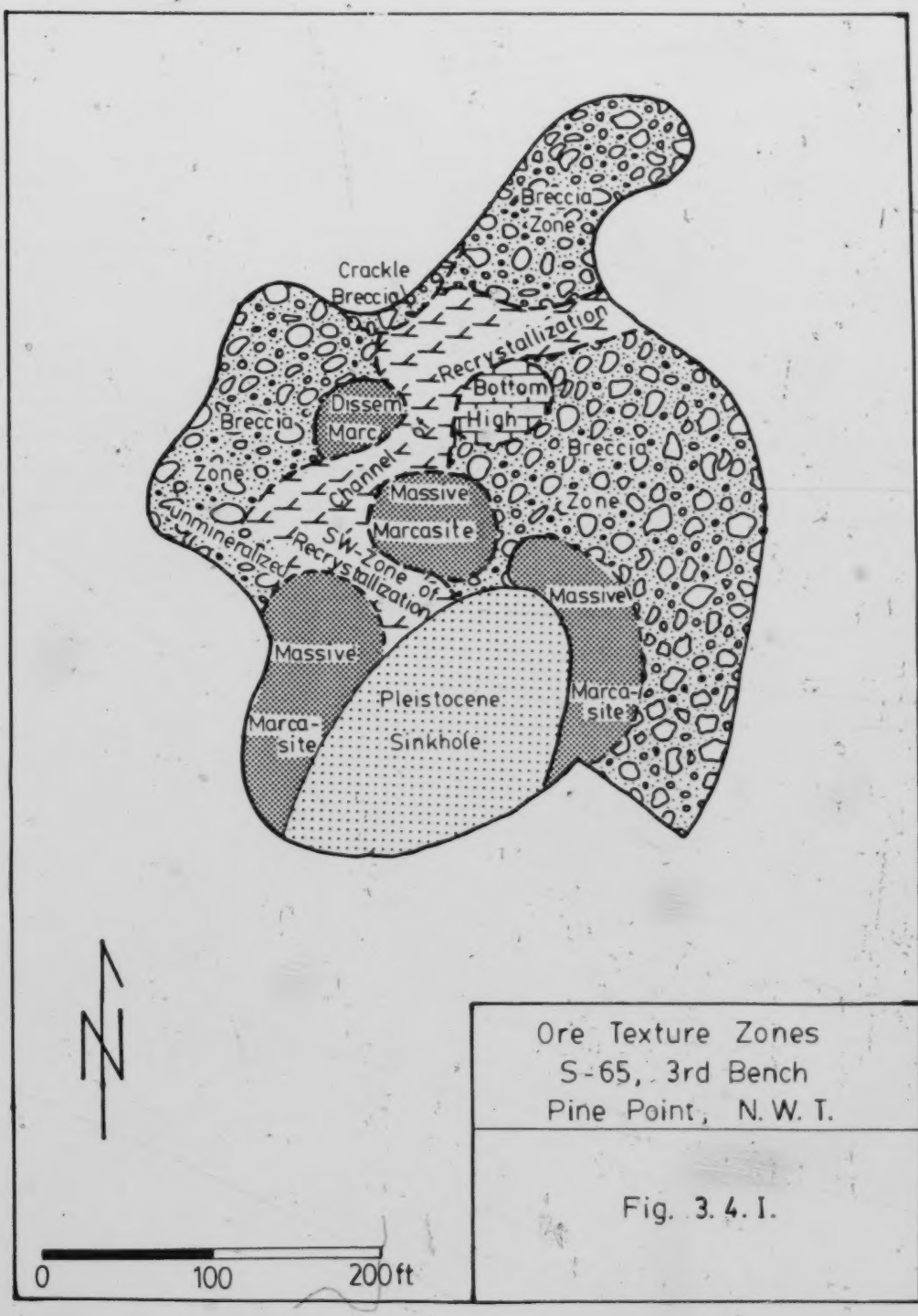
3.4 The Ore Textures on the Third Bench of S-65

Introduction

The mapping of the S-65 ore body so far described consisted of the geological mapping of the host rock. For the purpose of improved grade control during mining and for the better understanding of ore type zonation, the author also performed mapping of ore textures. The employment in the grade control department at Pine Point Mines Ltd. involved the frequent inspection of mining faces on the third level of the S-65 pit. The varying ore textures of this mining level were recorded and an ore texture distribution map was produced.

This ore texture mapping procedure of the third bench of the S-65 ore body lead to the recognition of characteristic ore texture zones in and near the ore body (Fig.3.4.I):

1. Breccia zone
2. Zones of marcasite concentration
3. Zones of coarse recrystallization
4. Detrital ore zones, including a Pleistocene sinkhole



Ore Texture Zones
S-65, 3rd Bench
Pine Point, N. W. T.

Fig. 3.4.1.

The Ore Textures in the Breccia Zone

The mineralized breccia zone of the third bench encompasses almost the entire north half of the mined bench. It is overprinted from the SW to the NE by an up to 10 m wide channel of recrystallization and boardered to the south by marcasite zones and a sinkhole. The maximum diameter of the breccia body is approximately 100 m.

The main collapse zone was formed by the infilling of one or more large cavities by breccia fragments and by mechanical and chemical deposition of carbonates and sulfides.

The breccia fragments in this main ore zone consist of recrystallized H, I and J-facies limestone, massive chunks of marcasite, internal sediments and fragments of the Watt Mountain Formation. The open spaces between the breccia fragments were infilled with ore material with great textural varieties. The breccia fragments and/or the matrix were often completely destroyed by later solution activity. The solutions caused textural overprinting by dissolution followed by redeposition of ore or host rock. Overprinting occurred as rebrecciation, internal sedimentation, sulfide and dolomite impregnation and recrystallization. Mineralization decreases towards the periphery of the breccia body and only sphalerite is found occasionally as fracture-fill in crackle breccias.

The breccia ore occurs in a great variety of textures. A classification of textures similar to that of Smith (1964) was used for the breccia zone. The theoretical, textural classification uses increasing complexities of crystal aggregates from primary, mono-mineralic to secondary (overprinted), poly-mineralic textures. This framework was then infilled using descriptive, genetic and other methods of classification.

Textures of the Main Breccia Zone:

PRIMARY TEXTURES

1. Mono-mineralic textures

a) Massive crystal aggregates, caused by:

- nucleation and growth of individual crystals in aggregates.
- mechanical accumulations of aggregates.
- recrystallization.

b) Peripheral, layered crystal aggregates, formed by:

- capping by crystal layers.
- rimming by crystal layers.
- crystal lining of fractures:
  comb texture.

- spherical or rounded crystal aggregates:
  - radiating textures
  - colloform textures

2. Poly-mineralic textures, caused by:
   - nucleation and growth of minerals of different composition
   - mechanical accumulations of minerals of different composition.
   - recrystallization
   - the effects of temperature changes
   - eutectic precipitation and growth

SECONDARY TEXTURES

1. Overprinting, seen as:
   - Mixed textures: Rebrecciation, internal sedimentation, sulfide and dolomite impregnation, recrystallization, etc.

PRIMARY TEXTURES

1. Mono-mineralic Textures

a) Massive Crystal Aggregates

Massive crystal aggregates can be the result of growth in place, mechanical accumulation or recrystallization. All three processes involve the formation

of triple junctions.

When after the seeding and settling of a crystal, the delivery of ions and complexes of the crystallizing substance continues, each crystal will continue to grow. The shape of the crystal will be determined by the requirements of space filling (obstructions), and by the tendency of minimizing interface and surface energy by reducing the size and number of high energy interface and surface area. This process of minimizing energy is called annealing.

One important feature of annealing is the formation of characteristic triple junctions between three grains or crystals. At the triple junction of an annealed, mono-mineralic substance mutual angles will approach 120° to minimize the interface energy equally in the three grains. Crystals with outlines that do not fit the 120° angle have to curve their boundary surfaces to permit a 120° angle at the tri-crystal junctions (Stanton, 1972).

These crystal mushes or mass structures are comparable to foam structures. Smith (1964) performed a large number of experiments with foam and explained the shapes of crystal polyhedra and the energies involved in the following way: In the foam models, the amount of curvature of a septum is proportional to the difference in gas pressure across it. In crystal mushes the interface curvature is proportional to the interfacial free energy

across it. The interfacial energy is larger across a curved as opposed to a straight crystal boundary, and crystal growth will be increased to straighten curved septa or interfacial boundaries in order to decrease the interfacial free energy and, thereby lower the total energy potential of the system in which a crystal grows. A massive, mosaic texture showing annealing in its triple junctions (120° angles) can be the result of the following processes (Fig.3.4.II):

a) During the growth of crystals in a crystal mush the crystal interfaces were adjusted to 120° triple junctions. Growth annealing can produce curved crystal interfaces.

b) The crystals were mechanically accumulated and the interstices filled by overgrowth. This process would produce straight interfaces and display overgrowth textures around the core of the crystals.

c) The triple junctions formed in the process of recrystallization in which case the crystal edges would also be straight. The interior of the crystals, however, would be uniformly clear.

Figure 3.4.II. Triple junctions between sphalerite crystals. (Scale: 1cm = 0.5mm)

b) Peripheral, Layered Crystal Aggregates

The coating of breccia fragments can occur as capping, rimming or lining of fractures.

Capping of the breccia fragments occurs when crystal nuclei form in solution. The same solution current transports the nuclei, which continue to grow at the same time in a super-saturated environment. When either the velocity of the current slows, or when the weight of the growing crystal exceeds the carrying capacity of the current, gravity settling and capping of the upper surfaces of the breccia fragments occurs. Figure 3.4.III shows sphalerite capping of a breccia fragment. Crystal growth continued after the gravity settling because impingement textures occur between neighboring, outwardly growing crystals. This impingement texture is common in capping or rimming ore textures.

Rimming of breccia fragments by growing crystals (Fig. 3.4.IV and 3.4.V) occurs when crystal nucleation happens on pre-existing mineral surfaces. This form of nucleation is more common than nucleation in suspension, because excess surface energy of the existing surface can supply some of the new crystal nucleation energy. As the nuclei, which form around the pre-existing minerals, are basically weightless, the process does not involve gravity settling and the result is a rimming, rather than a capping ore texture.

Figure 3.4.III. (Sample #017) Rebrecciation: Matrix supported breccia with sphalerite capping.

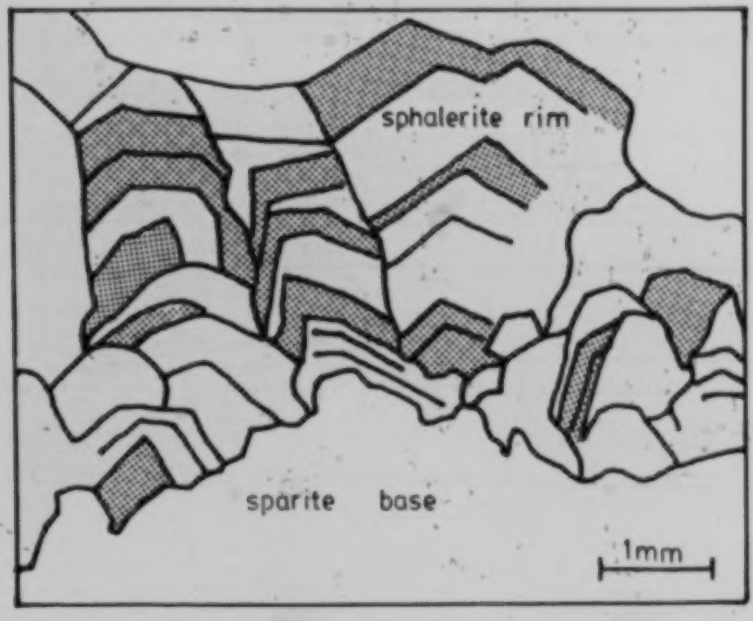


Fig.3.4.IV. (Sketch after Sample S-65-#3). Rimming sphalerite crystals. Favorably oriented, outwardly growing crystals impinge on others and increase in size.

The process of rimming involves the outward growth of neighboring crystals of different crystallographic orientation into open space, which then obstruct each other (impingement) and suppress the growth of less favorably oriented crystals. Figure 3.4.IV. is a sketch of such a favorably oriented crystal which typically increases in size suppressing the growth of neighboring crystals. Favorable faces can be those with greater surface energy and the growth of such faces will be fastest (Smith, 1964).

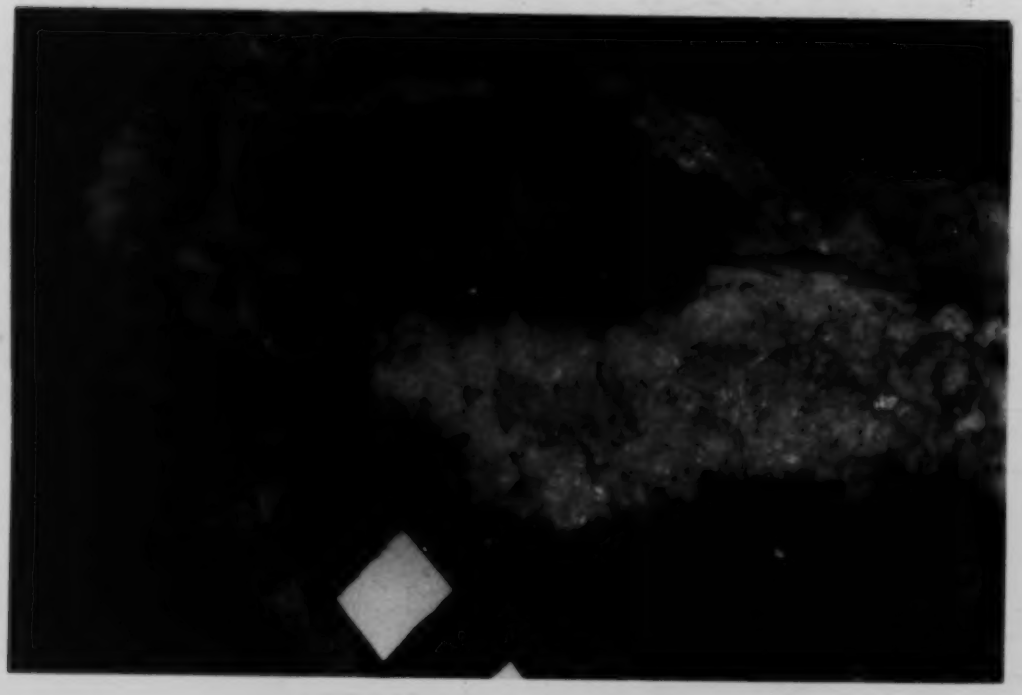


Figure 3.4.V. Sphalerite rimming of breccia fragment. (Scale bar in cm)

Fig.3.4.VI. (Sample S-65-#1/2) Round, framboidal aggregate or concretion. (Scale: 1cm = 0.5mm)

The lining of narrow open spaces or open fractures in a breccia by euhedral, prismatic crystals is called comb structure. This structure is the result of linear growth and mutual impingement.

Small mass structures can also be formed by impingement and growth processes. Spherical aggregates of compact, radiating crystals commonly grow around a nucleus of another substance and form in the above described manner. They are micro-crystalline to coarse crystalline concretions

or grain aggregates and spherical or columnar (stalactytic) in shape.

The regular form of such framboids suggested to various authors an organic origin (Love and Amstutz, 1966). They believe, that framboidal aggregates grew authigenically caused by sulfur bacteria or a replacement of a sponge like body (Fig.3.4.VI).

So called colloform sphalerite is an often described sphalerite ore texture and is another example for rounded, micro-crystalline grain aggregates (Fig.3.4.VII). Under conditions of rapid nucleation, the presence of large numbers of precipitating seeds prohibits the growth of large crystals. Instead aggregates of seeds or immature crystals will accumulate and tend to form rounded masses. These rounded shapes are the result of the minimizing of total energy of the whole aggregates. An example of such a rounded aggregate is the colloform growth of sphalerite. Even though individual crystals within the colloform aggregate have well developed crystal faces, or can show evidence of abrasion by mechanical transportation, the aggregates of many crystals have rounded forms. Roedder (1968) has presented ample evidence for the crystalline as opposed to colloidal origin of these ore textures. The coloring mechanism of colloform sphalerite is a combination of the iron, zinc and sulfur content, and the presence of organic compounds and impurities (Rhoedder, et al., 1968).

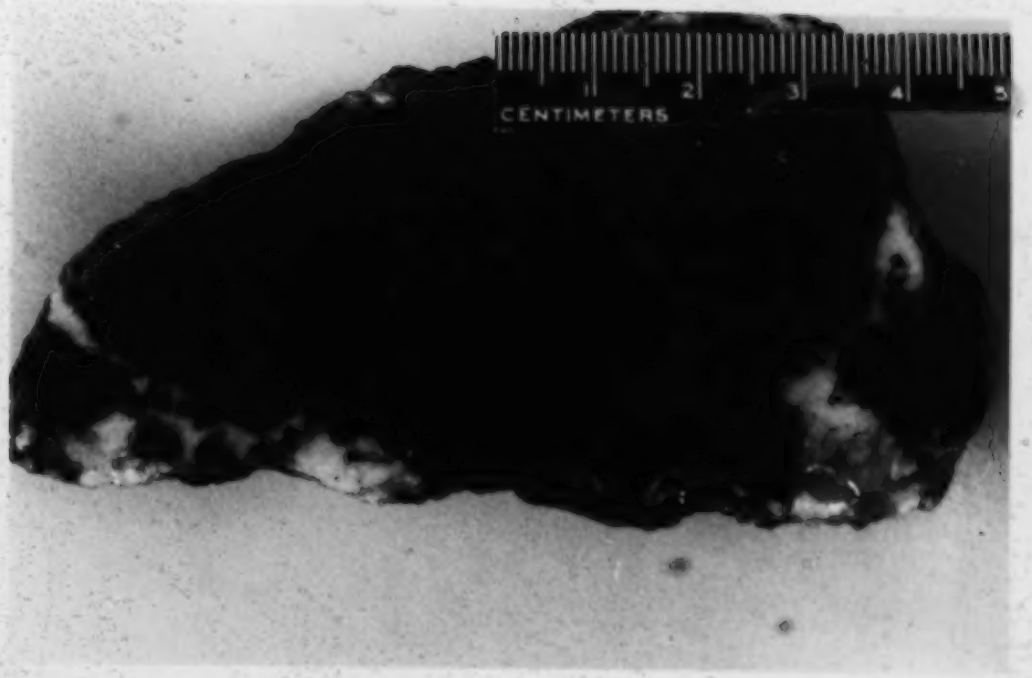


Fig.3.4.VII. Colloform Sphalerite

Only a few aspects of colloform texture will be discussed in this chapter. The growth banding of colloform sphalerite is concentric and parallel to the external shape. However, staining rims resulting from secondary solution diffusion can run obliquely or perpendicularly to primary banding. The nuclei of the spherical aggregates may be part of the wall rock but it does not seem to be necessary that

another mineral forms the core of the colloform mass. Various spherical masses of pure sphalerite were observed without cores of any foreign matter. The tendency of minute crystals to form spherical aggregates reflects an attempt to reduce total energy of the system besides reflecting a large number of nuclei and spatially uniform growth conditions. Instead of rapid nucleation, solution flow can also supply the minute particles for rounded crystal aggregates. The resulting aggregates are similar to colloform sphalerite textures. However, clear evidence of rounding by transportation of the constituting crystals is evident.

Pisolites and peloids are similar to spherical, colloform aggregates. Pisolites sensu strictu (i.e. a spherical or subspherical accretionary body over 2 mm in diameter) are shown on Figure 3.4.IIX. Smaller versions of pisolites are peloids. Kucha et al. (1990) described peloids as: elliptical to spherical bodies generally 20 - 90 microns in diameter, composed of a fine grained nucleus and a coarsely crystalline, dentate rim (corona). They are clearly differentiated from coated grains. Kucha et al. observed optical, chemical and size variations from the core to the corona. They concluded that because of the peloids' consistent composition, texture and structure they must originate from a general phenomenon like bacterial activity rather than being the result of inorganic precipitation. Layers of pisolites or pelites could form colloform type textures.

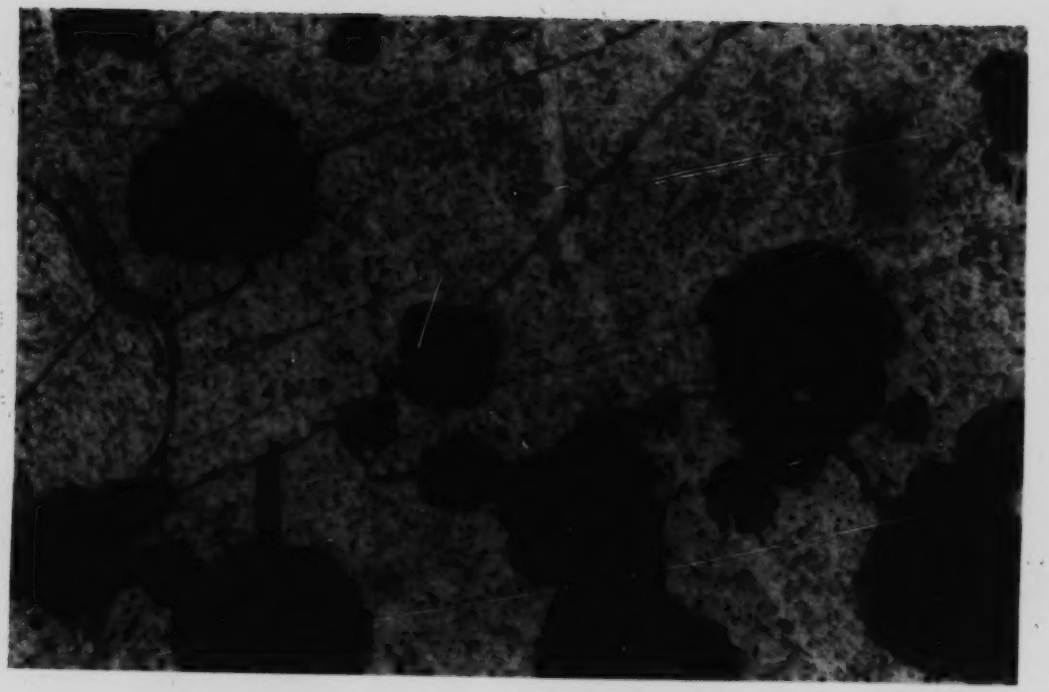


Figure 3.4.IIX. Pisolites and pelites in sparite

Scale: 1cm = 0.25mm

2. Poly-mineralic aggregates

Poly-mineralic aggregates can be formed by simultaneous growth or mechanical deposition of various phases. During growth and during later recrystallization the forming of triple junctions and the annealing of the phases become texture forming processes within the aggregates. For the purpose of this discussion, it is sufficient to deal with only two phase or duplex aggregates, because even in poly-mineralic system with more than two solid phases, the growth of a crystal is mainly influenced by only one neighboring crystal. The structure of such duplex aggregates depends on the energy difference across interfacial boundaries and the proportions of the two phases. Assuming one major phase "a" and a minor phase "b", phase "b" will grow at triple junctions of phase "a". This tri-crystal junction of phase "a" is most favorable because a large area of grain boundary is being eliminated. Energetically slightly less favorable is the growth of crystals of phase "b" along the grain edges of phase "a". Approximately twice as much of the interfacial energy, needed for the two crystal types above, would be required to grow phase "b" directly within the major phase "a" (Fig.3.4.IX).

With the introduction of a second phase, the mutual angle of 120° at a triple junction will change, depending on differences in interface energies. The dihedral angle theta of phase "b" is defined as the angle that a

crystal of phase "b" at a triple junction forms between two crystals of phase "a". This dihedral angle theta is characteristic for the two components of an annealed duplex aggregate.

Measurements of the dihedral angle of the phase "b" allow the estimations of the difference in interfacial energy across phase boundaries and grain boundaries. A phase boundary is the boundary between two grains of different phases ("a" and "b"), a grain boundary is the boundary between two crystals of the major phase "a". The three drawings on Figure 3.4.XI. show the relationship between dihedral angle and interfacial energies.

If the difference of interfacial energies is high, i.e. theta approaches 180°, then the minor phase will form equant, rounded grains. If the difference of interfacial energies is low, i.e. theta approaches 0°, the minor phase will grow in idiomorphic, cuspate or film like bodies.

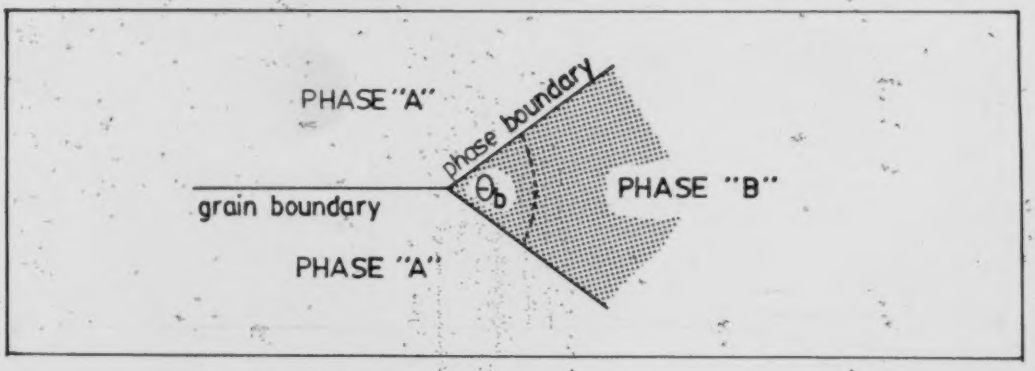


Figure 3.4.IX Sketch of a triple junction in a duplex aggregate and the dihedral theta angle of the phase "b".

Typical examples for such relationships are coexisting sphalerite and galena: Sphalerite as the minor phase in galena will grow in isolated, rounded masses, while galena as the minor phase in sphalerite will grow in a network of wispy, concave, idiomorphic shapes (Stanton, 1972). Such shapes are shown on Figures 3.4.X and 3.4.XI.

Low energy cusps or films are an important feature in a substance, because dissolution of this minor phase will create channels and permit flow through the system.

Another similar low energy condition occurs when a solution forms a low theta angle with a solid. This solution, as the minor phase, can completely surround the major, solid phase and will allow transport of matter through the interstices. Oil and water form different theta angles with the solids present in the system, and their influence on the system will therefore differ considerably. The theta angle of a solid or solution can be further decreased, possibly to 0°, by the presence of impurities in the solution. The resulting flow of solution around the crystals can facilitate dissolution of the major phase, and the planting of isolated idioblasts of a second, minor phase (Stanton, 1972).

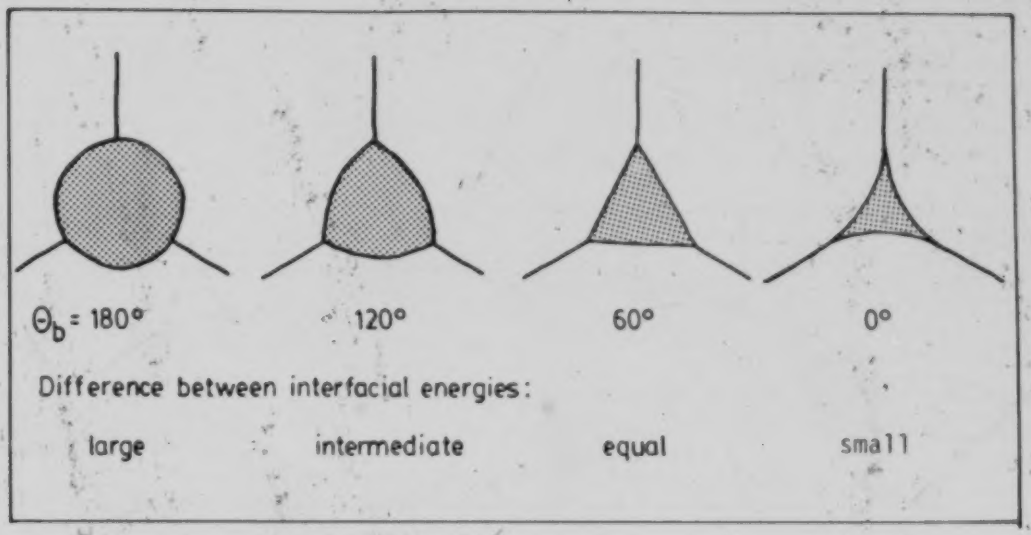


Figure 3.4.X. Sketch. The relationship between the dihedral angle and interfacial energies.

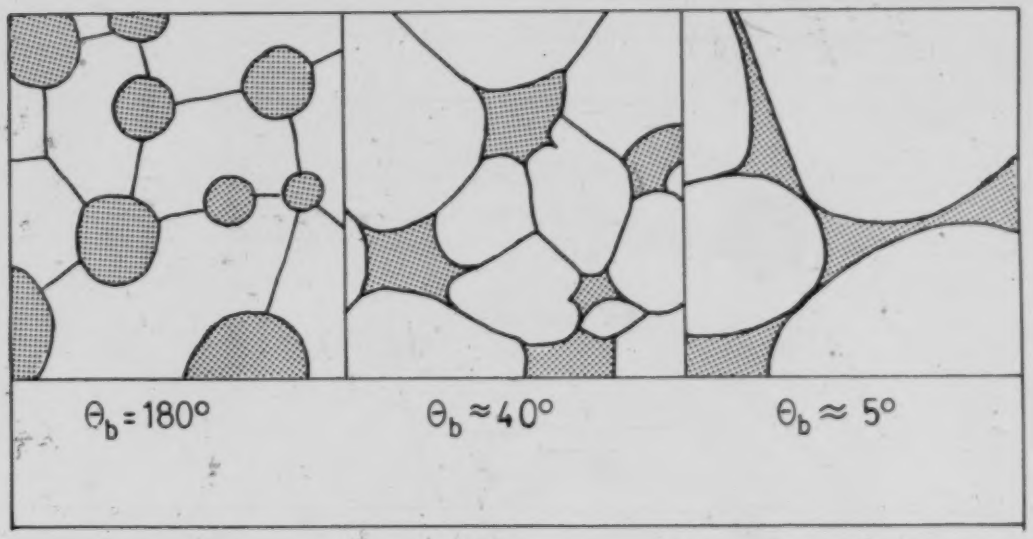


Fig.3.4.XI. Random duplex aggregates, characterized by unique dihedral angles (theta) at the triple junctions.

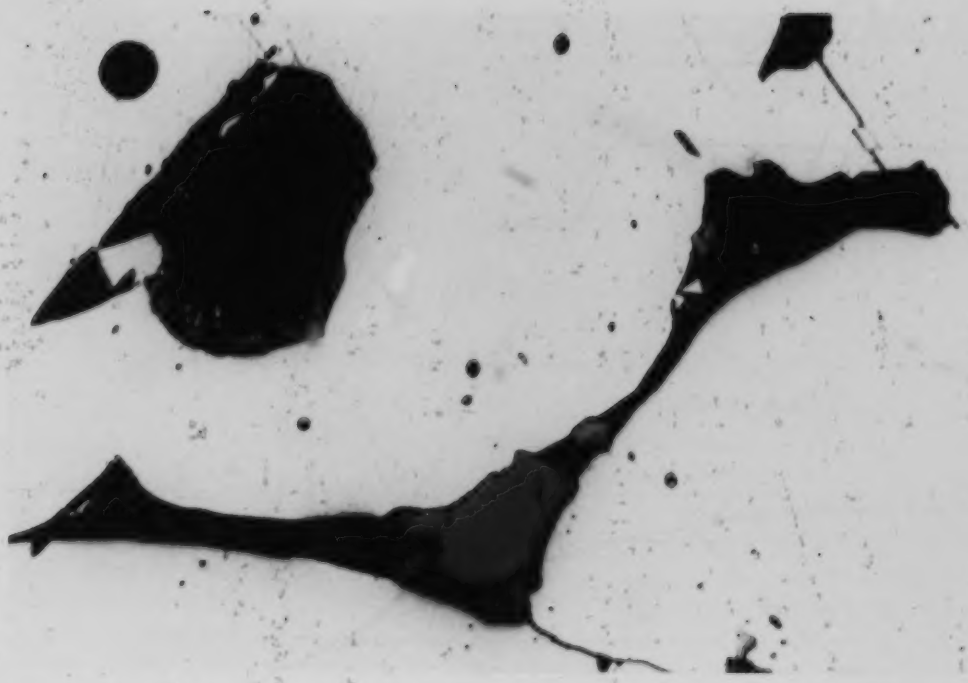


Fig.3.4.XII. Dolomite as the minor phase in galena. Cuspate dolomite partially replaced by sphalerite indicates a low angle theta. See also Fig.3.4.XI.
Scale: 1cm = 0.5mm

The Effects of Temperature Changes

Influences of changes in temperature have been shown to be of no importance for texture changes at low temperature.

Duplex structures formed by exsolution are most common at high temperatures. However, sphalerite is a very common host of exsolution textures and especially sphalerite-marcasite exsolution might occur even at low temperatures.

Eutectic Precipitation and Growth

Eutectic precipitation and growth is the contemporaneous formation of two or more solid phases at the expense of a liquid at a constant temperature. When two phases are supersaturated in solution, one of the phases will nucleate and grow first. This leads to the enrichment of the second component in solution, and to the decrease of the concentration of the first component in solution. The second phase will therefore nucleate and grow on top of the first. After a few reversals of this process, the result will be alternating layers of the two phases.

Another possible example of eutectic precipitation and growth is the rapid formation of dendrites by one of the two supersaturated components. The second phase can be entrapped between the branches of these dendrites and will solidify at a later time (Fig.3.4.XIII).

A third example of eutectic growth is seen when both supersaturated phases simultaneously form dendrites. The spacing between the branches will be controlled by diffusion and by the heat of crystallization. Surface energy and surface type (singular, vicinal or diffuse) will control the morphology of the dendrites.

Fig.3.4.XIII. Eutectic precipitation. Crystalline sphalerite entrapped in galena dendrite.
Scale: 1cm = 0.5mm

SECONDARY TEXTURES

1. Overprinting of Textures

Remobilization of minerals in the ore zones has changed textural features and complicates the identification of textural zones. For example, the zones of intense recrystallization and the marcasite zones represent overprinted parts of the main breccia zone.

An overprinting feature often observed in S-65 is the rebrecciation of ore internal sedimentation, sulfide and dolomite impregnation and recrystallization. At least two stages of rebrecciation can be observed on Fig. 3.4.III. The photograph shows breccia fragments whose former upper surfaces were originally capped by detrital crystals and are now randomly oriented. As another indicator of rebrecciation serves the differentiation between fragment supported and matrix supported breccias; An unaltered collapse zone can be expected to be fragment supported. Many parts of the S-65 ore zone, however, display matrix supported breccia textures (Fig.3.4.XIV).

Crackle Brecciation

In the S-65 ore body only very minor mineralization was found associated with the crackle breccia. Finely disseminated euhedral sphalerite and galena can occur in the sparite filled fractures (Fig.3.4.XV).

Fig.3.4.XIV. Matrix supported breccia.

Fig.3.4.XV. Crackle brecciation at the periphery of the S-65 ore body.

The Ore Textures of the Marcasite Zones

On the third bench marcasite enrichment occurs at four locations around the sinkhole and in the NW quadrant of the main collapse zone.

Massive marcasite replacement occurs at three of the four locations surrounding the sinkhole. The massive marcasite can occur as a breccia with marcasite fragments and sparite matrix.

Disseminated marcasite was found at the other two locations mentioned above and occurs in internal sediments as a detrital component or in recrystallized zones as impregnation.

Marcasite textures were summarized as follows:

1. Massive marcasite replacement
   - uniform massive
   - colloform
   - brecciated massive
2. Disseminated marcasite replacement

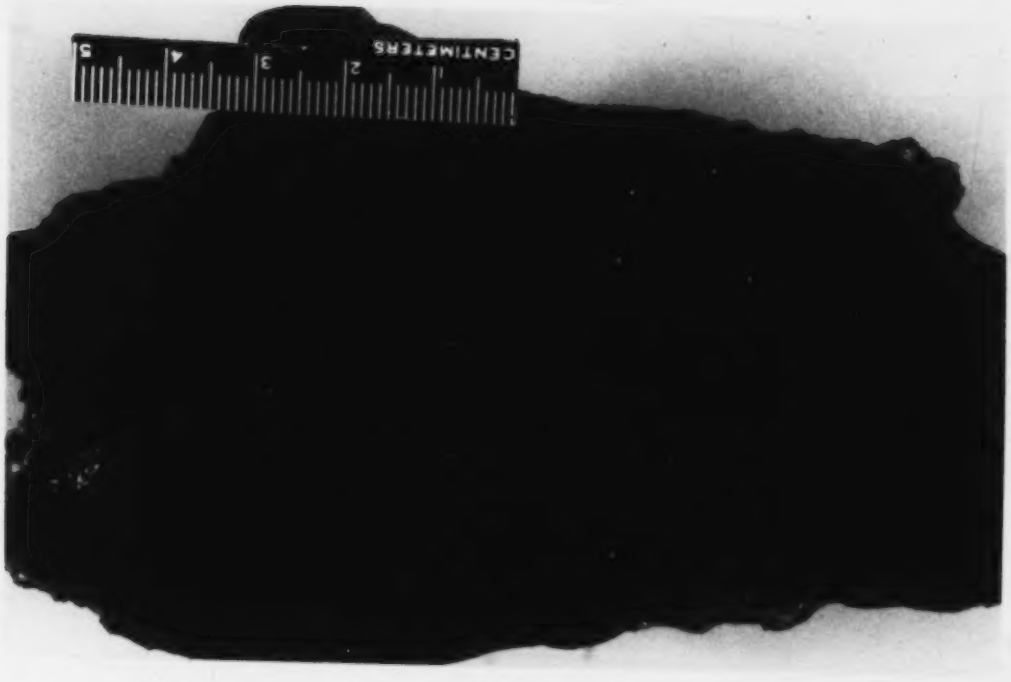
1. Massive Marcasite Replacement

Most common in these zones are meter sized patches of homogeneous, massive marcasite. The marcasite grains or crystals are very fine grained, which gives the rock an earthy look. Fractures occur irregularly without suggesting any bedding features.

Dehydration and compaction cracks are also found to be randomly oriented and display no bedding or lamination textures (Fig.3.4.XVI).

Occasional inclusions of sphalerite outline wavy or bulbous surfaces of marcasite aggregates similar to colloform sphalerite textures. This colloform marcasite texture (Fig.3.4.XVI) suggest rapid nucleation of marcasite and settling of these nuclei out of solution (Anderson, 1975). The massive, rounded marcasite aggregates were dehydrated and solidified before crystal growth could take place. Due to the metallic reflectance and the constant colour of marcasite, these colloform textures do not display the colour banding which is typical of colloform sphalerite. The interstitial sphalerite is medium grained and is detrital. The provenance of the sphalerite grains is very proximate because only very minor abrasion is evident.

When observing large scale textures in the massive marcasite zones of the ore body it becomes evident that migrating solutions first dissolved carbonates of an



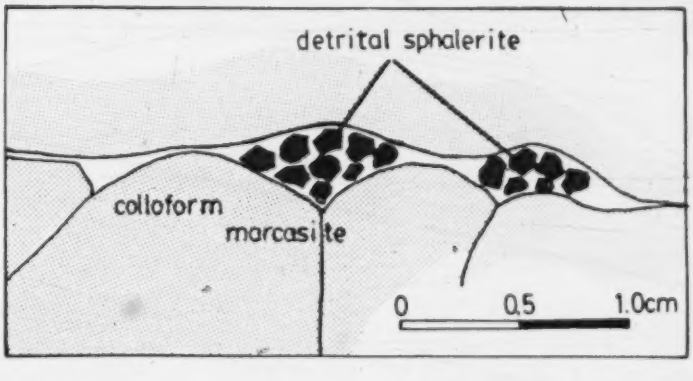


Fig.3.4.XVI.(Sample #013) Handspecimen of massive marcasite with dehydration and compaction cracks. Detailed sketch shows colloform marcasite with interstitial sphalerite.

existing sphalerite ore and subsequently filled the cavities with massive, colloform marcasite. After the dissolution of the host carbonate, sphalerite was unsupported and brecciation or mechanical transport over short distances occurred, before its poikilotopic enclosure by massive marcasite. In support of this theory of the formation of the marcasite zones is another marcasite sample. This hand specimen shows massive marcasite which has infilled open space between amphipora remnants, which in term were replaced by sphalerite (Fig.3.4.XVI). The history of mineralization of this rock is: first the replacement of the amphipora fossils by sphalerite, followed by the dissolution of the amphipora hosting carbonate and the infilling of the caves and cavities by marcasite.

2. Disseminated Marcasite

Fine grained to micro-crystalline, disseminated marcasite is found in the above mentioned zone in the NW quadrant of the ore body. Marcasite occurs in this zone as a cement and partially as a replacement around rounded patches of dolomite crystals and internal sediments (Fig.3.4.XVIII). Interstitial hydrocarbon is common and marcasite occasionally forms pseudomorphs after the tar like substance.

At a later stage of solution activity sphalerite was crystallized in this zone. The small to medium sized,

disseminated sphalerite crystals are euhedral and form a secondary cement in the internal sediments. Sphalerite crystal growth follows marcasite and occasionally replaces marcasite crystals.

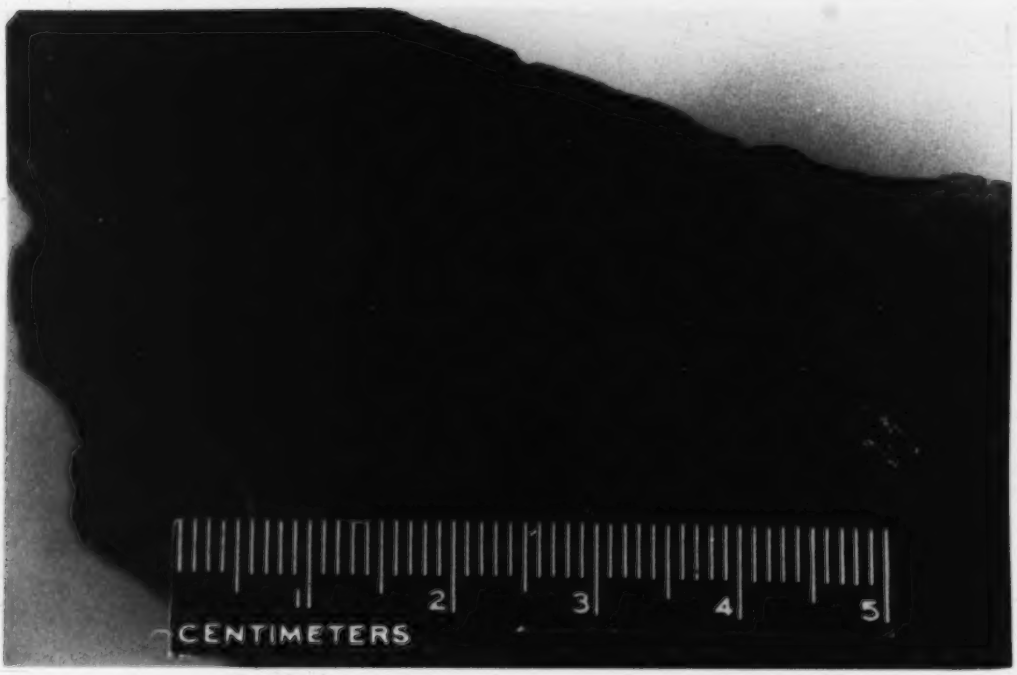


Fig.3.4.XVII.(#001) Replacement of dissolved amphipora by sphalerite. Host replacement by massive marcasite.

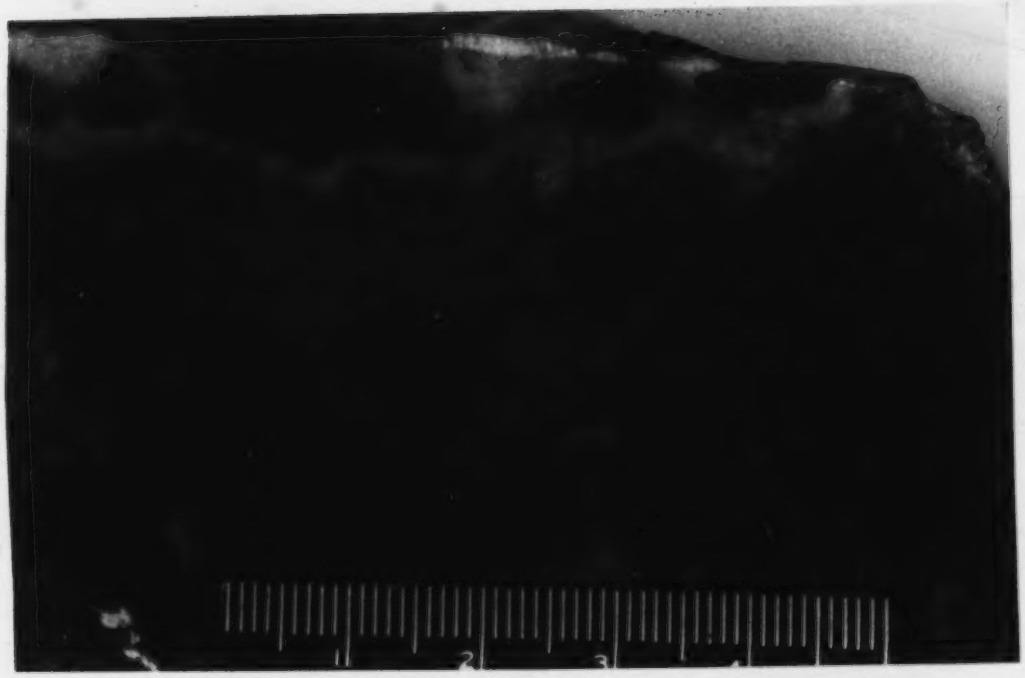


Figure 3.4.XVIII. (Sample 014) Disseminated marcasite. (Scale bar in cm)

The Ore Textures in the Zone of Intense Recrystallization

Recrystallization of the rocks on the third bench of S-65 is a very common feature and recognizable by the ubiquitous white and blue-grey sparite. Mapped as recrystallized ore zones were only volumes of rock which showed more than the usual amount of recrystallization and which contain characteristically recrystallized galena, sphalerite and marcasite ores. Such ore zones formed by recrystallization occurs as a winding, 5 to 10 m wide band in the northern part of the S-65 pit. Another zone of intense recrystallization but of very low ore grade is located in the SW of the S-65 ore body on the third bench (Fig.3.4.I). The zones of intense recrystallization have overprinted large parts of the previously formed ore textures of the breccia zone.

Typical ore textures related to recrystallization are:

1. Textures related to nucleation
   - budding
2. Textures related to primary recrystallization
   - fine mosaic texture
3. Textures related to normal growth
   - equidimensional foam texture
4. Textures related to secondary recrystallization
   - sphalerite stars
   - coarse crystal aggregates

Recrystallization is a process that reduces the amount of energy or strain in a crystal or in aggregates of crystals Stanton (1972) has recognized 4 stages of recrystallization: Nucleation, primary recrystallization, gradual growth and secondary recrystallization (coarsening). Figure 3.4.XIX shows the stages of gradual growth and coarsening of recrystallizing carbonate.

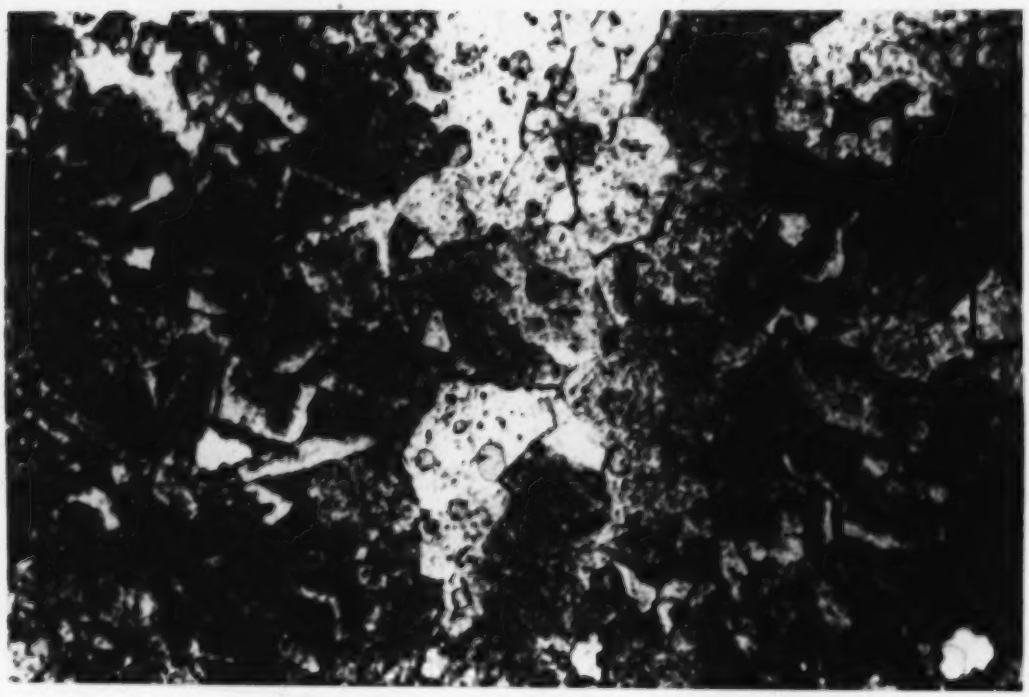


Figure 3.4.XIX. (Sample #026) Recrystallizing carbonate: From the outside to the centre of the photo: Stages of gradual growth and coarsening.

1. Nucleation as the initiation of recrystallization can happen in four possible ways:

a) A new, very small, seed like nucleus forms at the location of high strain.

b) Unstrained parts of the lattice expand and replace the strained parts.

c) Large volumes of strained mineral gradually change at the same time.

d) An unstrained, bud like extension of one crystal forms at a grain boundary or triple junction. During further expansion, the budding and the intruded grain are replaced.

In the ore bodies studied at Pine Point, sphalerite was observed to nucleate (or initiate) recrystallization using the processes a, b and c. Galena was observed to nucleate by growing bud like extensions (d) (Fig.3.4.XX).

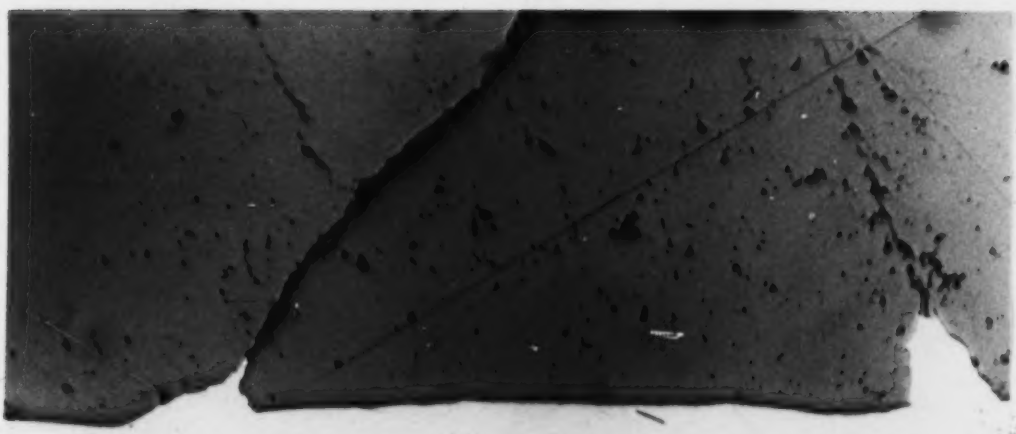


Figure 3.4.XX. (Sample #c2/4) Budding of galena into a triple junction with two sphalerite crystals. Nucleation stage of recrystallization. (Scale: 1cm = 0.1mm)

2. Primary recrystallization is the stage of progressive replacement after nucleation until the forming crystals impinge upon each other. These recrystallized grains are smaller in volume and are softer than the original mineral. Multiple nucleation commonly results in a mosaic texture with growth impingement boundaries which is an unstable configuration of crystals.

3. Normal, gradual grain growth, the third stage of recrystallization, removes these unstable boundaries by growing larger crystals. In this stage of recrystallization the growth of slightly curved crystal boundaries is attempted to decrease the energy level of the system. This stage of normal grain growth leads to the formation of equidimensional grains or an equidimensional foam texture.

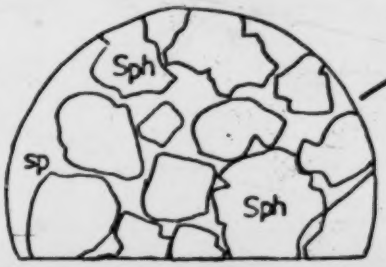
4. Secondary recrystallization, the fourth stage of recrystallization, results in further coarsening of the rock texture. Crystals with crystallographically unstable boundaries grow rapidly forming larger grains in a finer grained matrix.

Figure 3.4.XXI. shows various stages of recrystallization of a sphalerite ore fragments in a breccia. The outer layers of the sphalerite fragments are intensely recrystallized up to the stage of secondary recrystallization with large crystals in a finer matrix. Further into the breccia fragment the degree of recrystallization decreases to the stages of primary

recrystallization and normal growth with a mosaic texture and rounded crystal boundaries. In the centre of the breccia fragment the sphalerite grains are unaltered.

Recrystallization can be inhibited by the occurrence of another phase which will form a separating layer between two grains of the same mineral. In this way the union of two grains and consequently an increase in grain size can be inhibited.

1.)

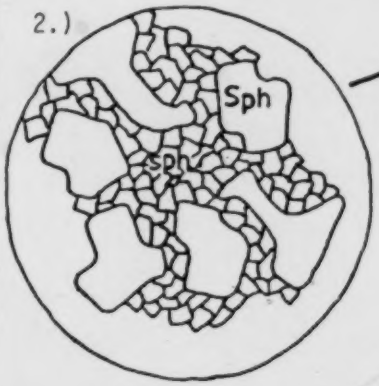


NON-RECRYSTALLIZED interior of a breccia fragment. Sphalerite crystals (Sph) possibly of detrital origin are cemented in sparite (sp).

0 01 0.2mm

Figure 3.4.XXI (Sample #003) Rebrecciated sphalerite ore fragments in the zone of intense recrystallization.

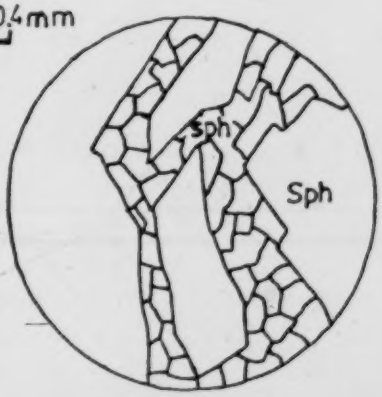
2.)



PRIMARY RECRYSTALLIZATION AND NORMAL GROWTH. Multiple nucleation created a mosaic textured sphalerite (sph) ground mass. Normal growth rounded the surfaces of the larger crystals (Sph).

0 0.2 0.4mm

3.)



SECONDARY RECRYSTALLIZATION. Large sphalerite crystals (Sph) in fine sphalerite matrix (sph).

0 .1 2mm

The marcasite concentration on the NW side of the ore zone occurs as disseminated marcasite in intensely recrystallized rock. Disseminated sphalerite can coexist with marcasite in this zone. Recrystallization shown on Figure 3.4.XXII shows only small, patchy remnants of the original host rock, which remind with their light beige colour on material of the J-facies which forms the bottom of the S-65 pit. The grey and white sparite are the result of complete replacement of the host rock. Marcasite growth appears to be late, as it is associated with fracture-filling, white sparite. Sphalerite and galena recrystallization is recognizable by the development of large crystals (normal growth stage of recrystallization) with crystals impinging upon each other (Fig.3.4.XXII).

In this zone, the most characteristic ore texture formed by recrystallization is isolated sphalerite crystal aggregates, which the author named "sphalerite stars". Such aggregates usually occur in white or grey sparite. These sphalerite stars are found especially frequently at the outer edges of this ore zone. The sphalerite crystals of a star are indicative of the fourth stage of recrystallization (i.e. secondary recrystallization) because they have considerably increased in size. Sometimes a sphalerite star is even made up of only one crystal (Fig.3.4.XXIII).

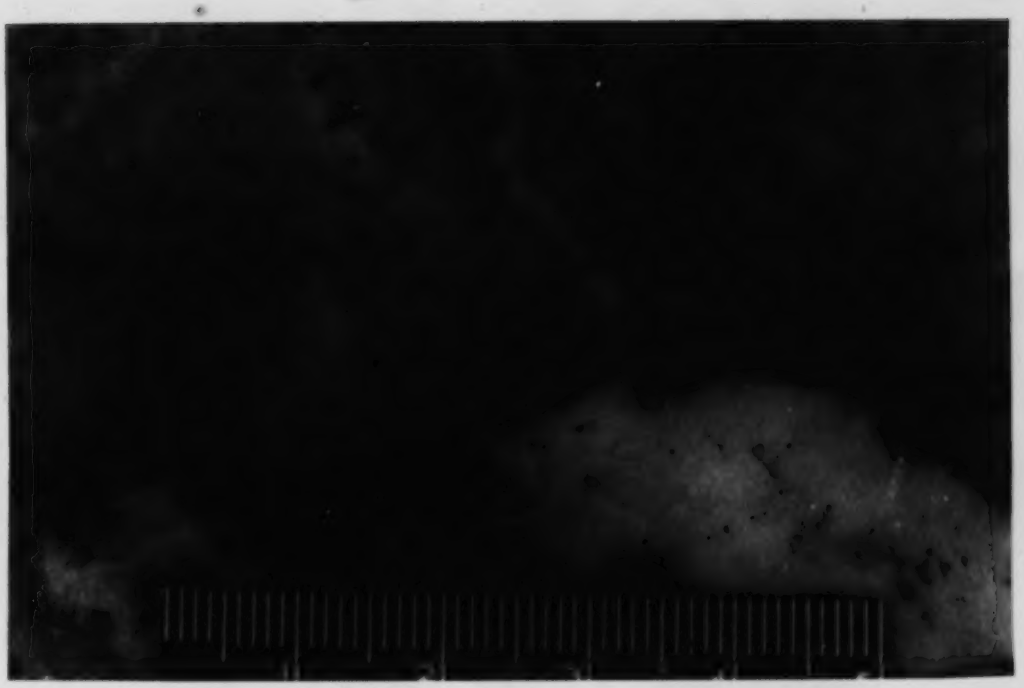


Figure 3.4.XXII Disseminated marcasite in intensely recrystallized sphalerite ore. (Scale bar in cm)

Figure 3.4.XXIII. (Sample #006) Sphalerite star in the zone of intense recrystallization.

Annealing twinning can be observed in some sphalerite crystals that make up a star. Such twinning occurs when a high energy boundary between two neighboring crystals, which is close to a twin orientation, is transferred into this twin boundary as an easy way to reduce energy. This is a reordering process that occurs during primary growth or recrystallization (Fig.3.4.XXIV).

Figure 3.4.XXIV. (Sample #7/17) Annealing twin in sphalerite star.

The degree of recrystallization in this ore zone increases further into the ore body. This is indicated by the joining of disseminated grains, the occurrence of large crystals and mosaic sulfide ore textures. Fig.3.4.XXV shows an example of galena in the third or fourth stage of Stanton's classification. Typical is the joining of disseminated galena crystals in order to form coarse crystals.

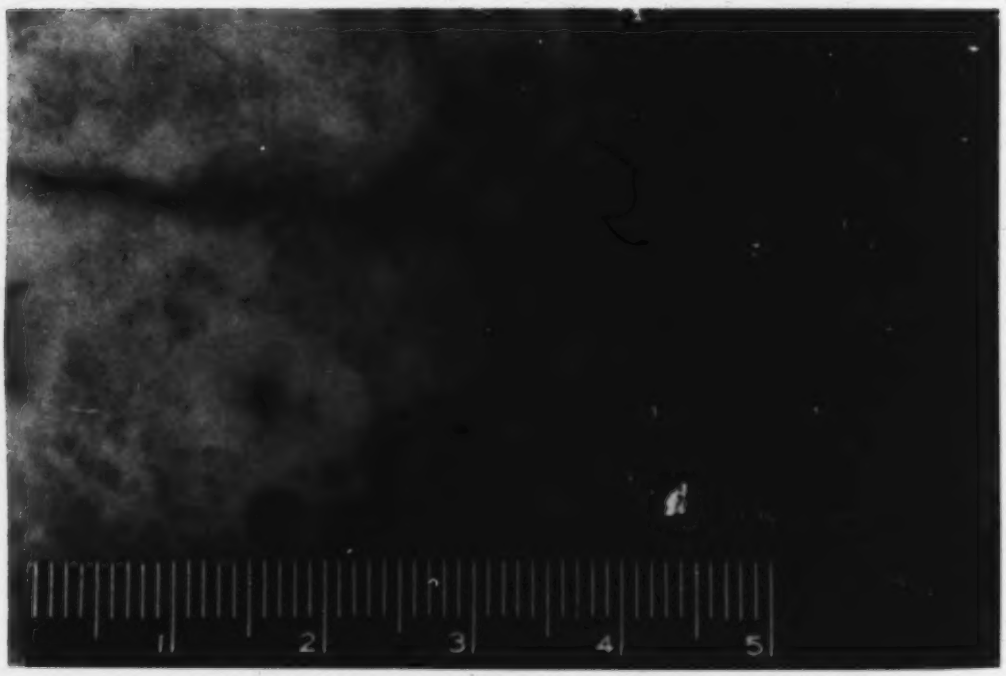


Figure 3.4.XXV. (Sample #018) Recrystallizing galena in the normal growth and secondary stage of recrystallization. (Scale bar in cm)

Calcspar and dolspar and associated sulfides do not only occur as replacement of previously formed rock but also as open space filling. Crystal growth during recrystallization combined with new crystal growth from solution exerted pressure on surrounding material which consequently fractured. Fracturing on this scale is not indicative of tectonic activities.

Where recrystallization channels cross the Fe enriched zone, interesting textural mixtures occur. Figure 3.4.XXVI shows marcasite and sphalerite disseminated in a breccia fragment, while recrystallizing galena is associated with the cross-cutting sparite.

In the SW of the ore body occurs a zone with intense recrystallization. After brecciation and open space filling by growing carbonate crystals and internal sediments, this zone was fractured, recrystallized, and open spaces were filled with white sparite. Occasional sphalerite crystals similar to the sphalerite stars, mentioned above, are commonly associated with dark grey sparite. However, the mineralization is of such a low grade that the area was named the SW-low.

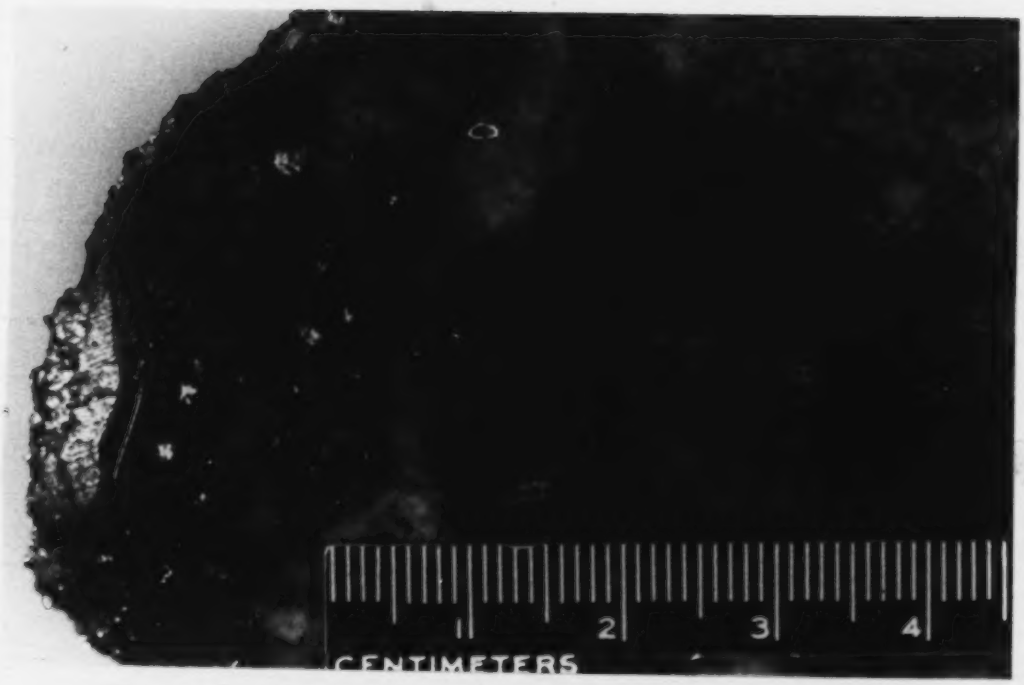


Figure 3.4.XXVI. (Sample #009) Textural mixture. Marcasite and sphalerite disseminated in a breccia fragment. Recrystallizing galena is associated with the cross-cutting sparite.

Ore Textures Formed by Detrital Sedimentary Processes and Diagenesis

As previously mentioned, primary crystalline ore textures are overprinted by later redistribution and ore-forming processes. Mechanical erosion, transportation and detrital redeposition is one possible sequence of events causing such overprinted ore textures. On the third bench of the S-65 ore body, such detrital sedimentary ore textures are common in all ore zones: After the initial forming of the collapse zone, initial sediments filled some of the open spaces between breccia fragments. The zone of recrystallization shows evidence of open space filling and sedimentary processes must have been involved. On a meter scale, the marcasite zones of the ore body are occasionally layered, suggesting sedimentary environments of deposition. The most typical sedimentary ore textures are present in the Pleistocene sinkhole and Pleistocene tunnel fillings. Throughout the whole ore body, material was continuously either chemically or mechanically distributed, whenever solutions opened up a karst system. After the deposition of the internal sediments, diagenetic processes cemented, infilled and replaced the sedimentary ore textures.

The ore textures which are related to detrital sedimentary processes and diagenesis are the following:

1. Textures formed by transportation and deposition from traction currents:
   - Abrasion and rounding of particles
   - Sorting (Degree of maturity)
   - Lamination
   - Compaction and pressure solution
2. Textures related to diagenesis of detrital ore
   - Cementation
     - by spary calcite or dolomite
     - by overgrowth
     - by encrustations (Pisolithic crusts)
     - by poikilotopic cementation
     - by pore and fracture-filling with sparite or ore
   - Replacement or displacement
   - Deformation

1. Transport and Deposition from Traction Currents

Galena, sphalerite and marcasite grains can be eroded by ground water passing through karst systems. After separation from the parent rock, the sulfide grains are abraded and sphericity and roundness are increased. Sphalerite grains with good roundness and a high sphericity index are common in healed fractures. Under higher magnification, pitting and fracturing due to transport and

abrasion can be recognized. Figure 3.4.XXVII shows sphalerite grains cemented by sparite. These grains are highly angular and poorly rounded and sorted, which indicates a short time and distance of transport.

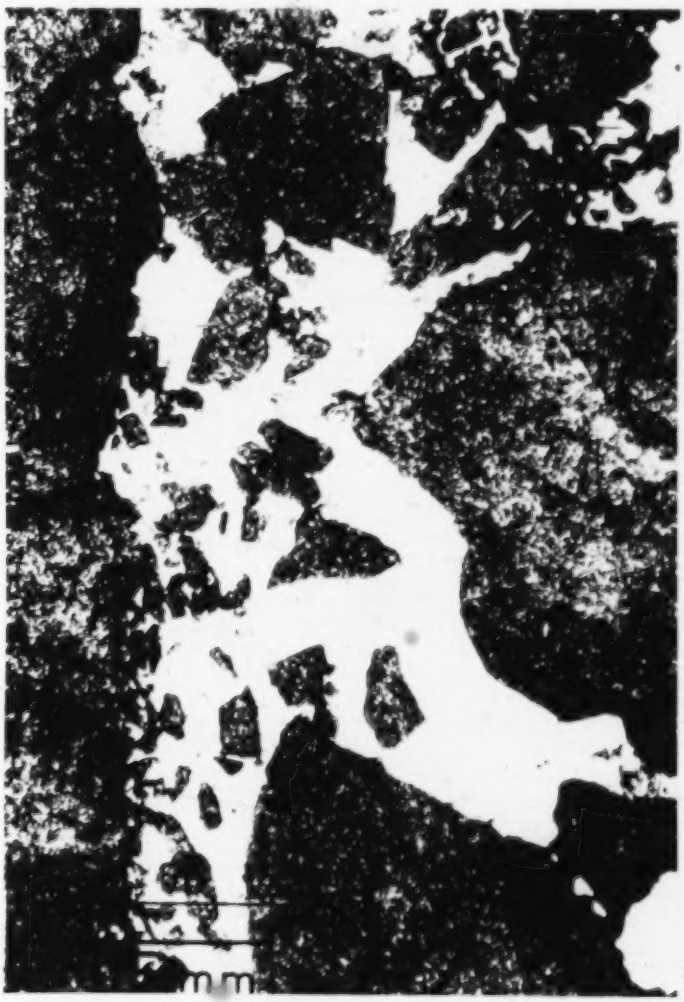


Figure 3.4.XXVII. (Sample #1/21) Angular sphalerite grains being transported. Cemented in sparite filled fracture.

2. Diagenesis of Detrital Ore

Cementation by spary calcite or dolomite is the most obvious diagenetic feature throughout the whole ore body. However, some other types of cementation are present, such as crystal overgrowth, pisolitic crusts, poikilotopic cementation and pore and fracture-filling. Other ore texture forming diagenetic processes in the S-65 ore are replacement, displacement and deformation.

Cementation and Accretions

If a transporting solution continues to supply ions and complexes to detrital crystals, growth on the crystal surfaces can continue as an overgrowth. If a crystal grows into open space, it will develop idiomorphic overgrowth with euhedral crystal faces (Fig.3.4.XXVIII). Particles trapped along crystal faces or grain boundaries and different coloring of the sphalerite generations aid in the recognition of overgrowths.

Encrustations similar to pisolitic crusts are a common form of cement in the Pine Point ores. A detrital pisolitic rim is shown on Figure 3.4.XXIX. In this case the constituent particles are angular, equant crystals with very low sphericity and roundness.

Poikilotopic cementation is also common in the Pine Point ores. It can occur as an inclusion within a crystal or as a patchy cement; the latter type indicates irregularly distributed nuclei.

Figure 3.4.XXVIII. (Sample #6/33 and 107) Idiomorphic overgrowth of sphalerite

When sulfides crystallize in porous cavities, the resulting ore textures depend totally on the size, and shape of the original pore space. Interstitial or inter crystalline cementation are very common. The filling in of pore space and fractures between sulfide mineralization by

calcite or dolomite cement produces distinct and characteristic ore textures. Also characteristic is the reverse ore textures, with sulfides filling fractures in sparite (Fig.3.4.XXXI).

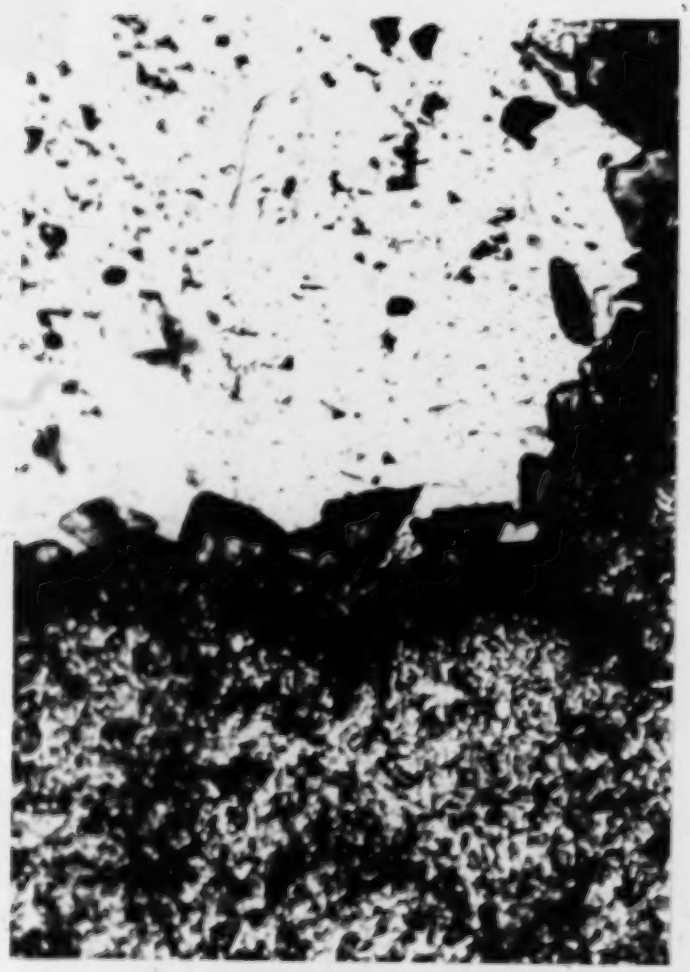


Figure 3.4.XXIX. (Sample #1/6) Detrital pisolitic rim of sphalerite. (Scale: 1cm = 0.1mm)

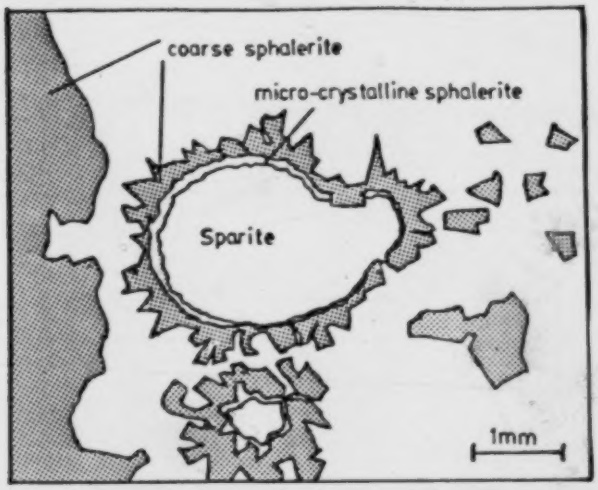


Figure 3.4.XXIX (Sample #2/17) Sketch of a subspherical true sphalerite pisolitic crust around a sparite core.

Figure 3.4.XXXI. Sphalerite as fracture-fill (Scale 1:1)

Replacement or Displacement Textures

In the repetitive processes of ore dissolution new formation processes such as replacement or displacement are important to the development of characteristic ore textures.

Authigenic replacement occurs, for example, in the transitional zone between unaltered host rock and the mineralized collapse zone. In this zone authigenic marcasite takes on a shard-like form because it replaces intergranular hydrocarbons. At a later stage, this marcasite is itself replaced by sphalerite (Fig.3.4.XXXII).

Authigenic displacement is a physical breaking and removal of matter by a growing crystal mush. Fig.3.4.IIXL shows sphalerite being displaced by sparite. Replacement or displacement textures can be recognized by cross cutting textural relationships and "ghost textures", which are textures in which the micro-texture has been destroyed but the macro-texture is preserved.

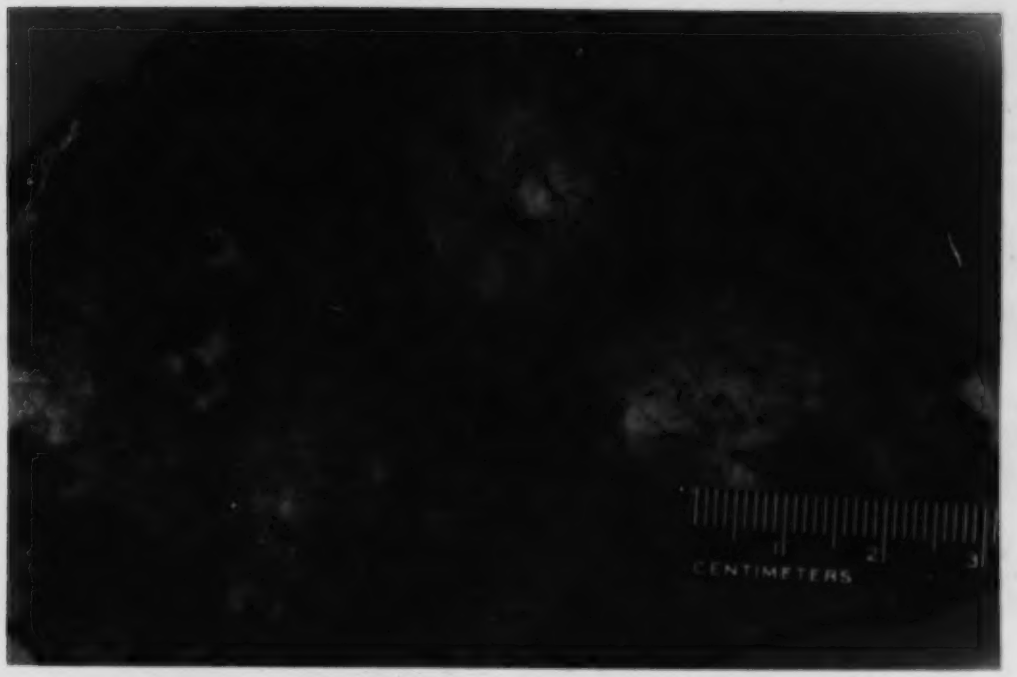


Figure 3.4.XXXII. (Sample #c/x) Disseminated sphalerite as secondary cement.

Deformation Textures

Brecciation, crystal growth and sedimentary loads exert pressures on adjacent ore or hostrock and result in deformation textures on macro- and microscopic scales. Mineralized fractures are indicative of former fracture porosity (Fig.3.4.XXXI).

Intense deformation twins in fractures or growth twin deformation are indicative of syn-deformational crystallization (Fig.3.4.XXXIII).

Another type of deformation texture is formed by fractures radiating away from a point of collision of two grains.

Grain compaction and pressure solution are common in massive ore layers. An irregular line contact at grain boundaries is the common result of compaction (Fig.3.4.XXXIV). Stylolytic solution surfaces with varying amplitudes and stylolite solution zones are the result of pressure solution and occur along compaction boundaries (Fig.3.4.XXXV).

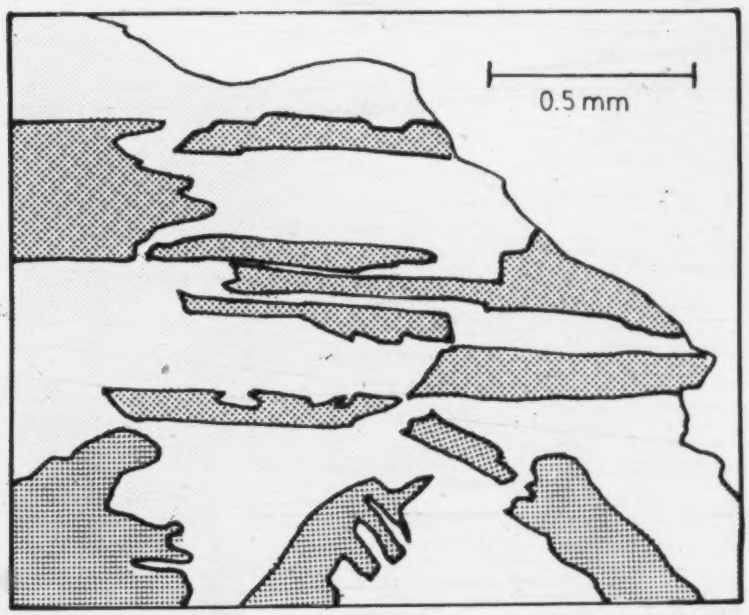


Figure 3.4.XXXIII. (Sample #2/15) Deformation twin in sphalerite crystal. (Sketch after photograph).

Figure 3.4.XXXIV. (Sample #1/14) Grain compaction in sphalerite crystal aggregate. (Scale: 1cm = 1.0 mm)

Figure 3.4.XXXV. Pressure solution of sphalerite crystals. (Scale: 1cm = 0.5mm)

Ore Textures in the Pleistocene Sinkhole

The greatest variety of sedimentary ore textures was found in the Pleistocene sinkhole. Figure 3.4.XXXVI shows a sample of laminated ore which occurs between glacial boulders. The laminated ore was formed by flow processes which separated grain fractions and minerals (Fig.3.4.XXXVII). The layers comprise detrital sphalerite, marcasite and minor galena. Calcspar, dolspar and marcasite are cementing minerals. There is no clay content, the grains are mostly angular and sorting has taken place. These features make this sediment sub-mature. On figure 3.4.IIXL a fracture-fill in a coarser sphalerite sediment is observed. The rock sample originates from the same sinkhole. The coarse (0.25-1.0mm) sphalerite grains on top and at the bottom of the picture were compacted. This compaction caused pressure solution. Later the sediment was fractured along bedding planes and fine grained sphalerite and calcite lined the fracture. The uniform thickness of this lining suggests chemical rather that detrital origin of the crystals. The fracture was later filled with sparite and another sphalerite generation. The expanding sparite crystals forced the fine grained lining off the coarser sphalerite grains and moved the band into the mass of sparite.

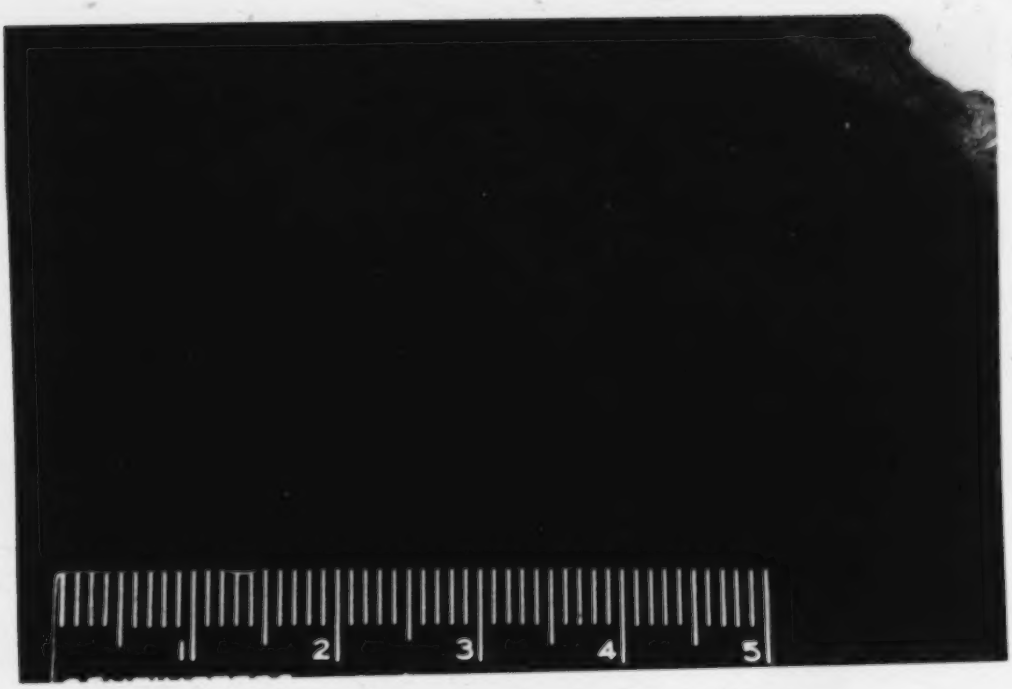


Figure 3.4.XXXVI. Laminated sulfide ore in Pleistocene sinkhole.

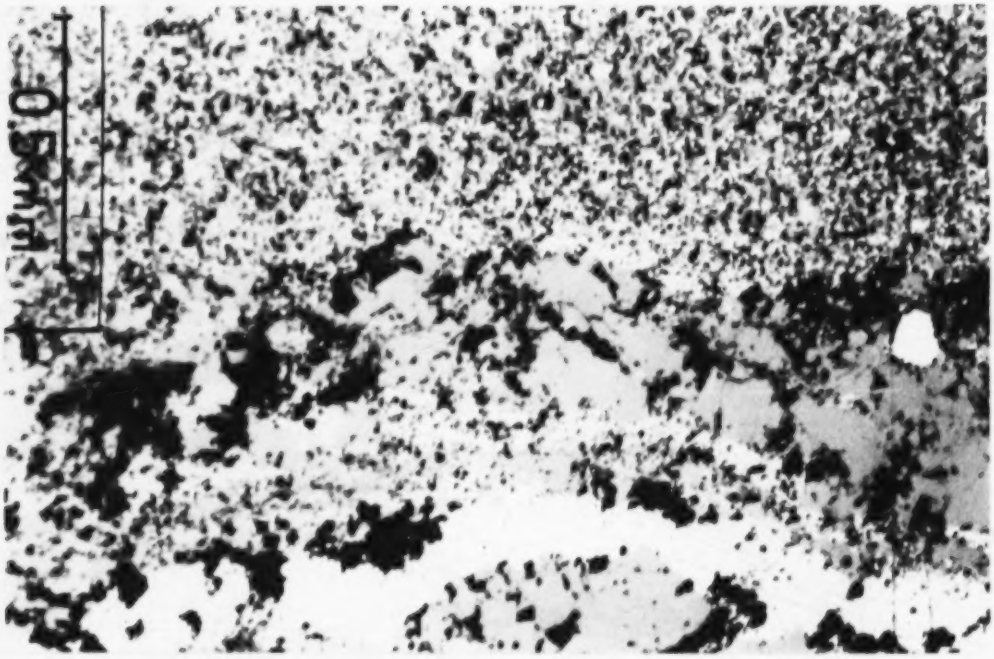


Figure 3.4.XXXVII. (Sample #2/17) Submature internal ore sediment. Pleistocene sinkhole.

The amount of marcasite present varies from layer to layer, which suggests that the marcasite was deposited simultaneously with the internal sediment. A closeup on this marcasite on Figure 3.4.IXL shows post-depositional interaction between marcasite and sphalerite. In this layer the marcasite is replacing portions of the

Figure 3.4.IIXL. (Sample #2/16) Thin sphalerite crytal rims or caps are lifted off their base by the growth of coarse sparite. Pleistocene sinkhole.

sphalerite grains. This indicates that solutions at Pleistocene times were supersaturated in iron and undersaturated in zinc which caused the dissolution of sphalerite. Precipitation of sphalerite out of solution at other locations in the Pine Point area is, therefore, quite

possible. Figure 3.4.XL is a photograph of micro-crystalline galena in layers with rounded surfaces. The surfaces of these wavy layers are marked by impurities and have a typical bulbous appearance strikingly similar to colloform sphalerite.

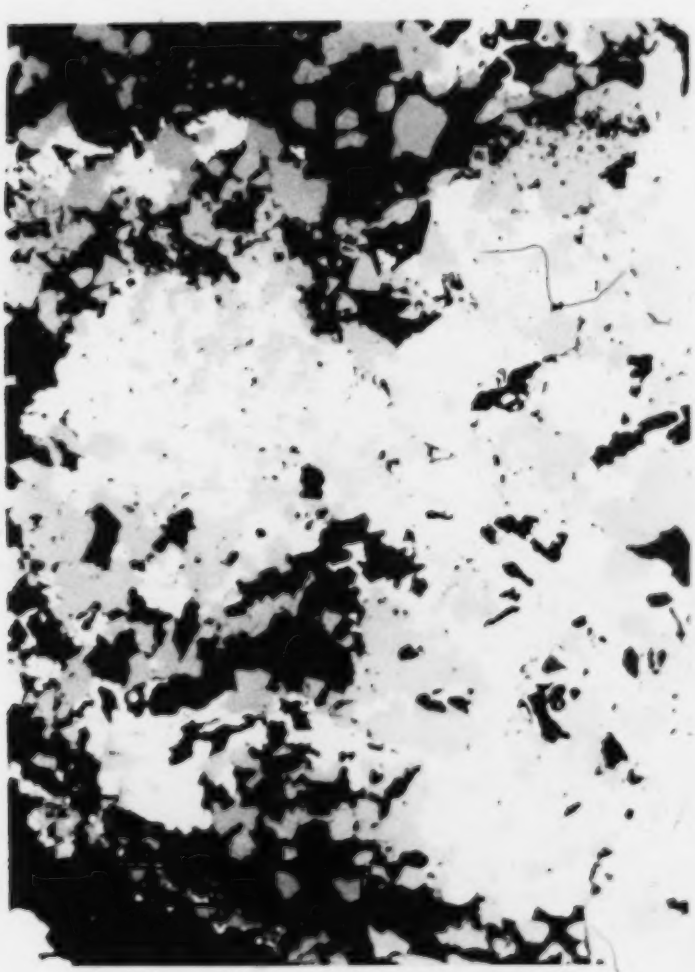


Figure 3.4.IXL. (Sample #2/14) Marcasite replacing sphalerite. Pleistocene sinkhole.

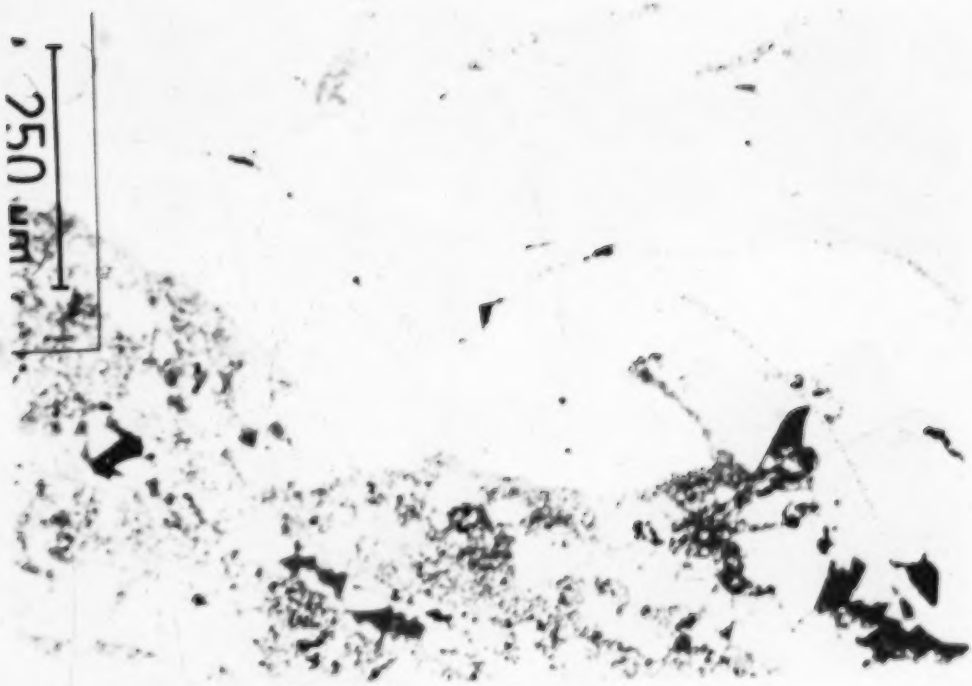


Figure 3.4.XL. (Sample #2/25) Colloform Galena. Pleistocene sinkhole.

Summary of Ore Textures of S-65

The following tables summarize the textures of sphalerite, galena and marcasite grouped into characteristic ore zones:

Textures of the Main Breccia Zone:

PRIMARY TEXTURES

1. Mono-mineralic textures

a) Massive crystal aggregates caused by:

- nucleation and growth of individual crystals in aggregates.
- mechanical accumulations of aggregates.
- recrystallization.

b) Peripheral, layered crystal aggregates formed by:

- capping by crystal layers.
- rimming by crystal layers.
- crystal lining of fractures:
  comb texture.
- spherical or rounded crystal aggregates:
  radiating textures
  colloform textures
  including pisolites/pelites

2. Poly-mineralic textures caused by:
   - nucleation and growth of minerals of different composition
   - mechanical accumulations of minerals of different composition.
   - recrystallization
   - the effects of temperature changes
   - eutectic precipitation and growth

SECONDARY TEXTURES

1. Overprinting seen as:
   - Mixed textures: Rebrecciation, internal sedimentation, sulfide and dolomite impregnation, recrystallization, etc.

Textures of the Marcasite Zones:

1. Massive marcasite replacement, with subtypes:
   - uniform massive
   - colloform
   - brecciated massive
2. Disseminated marcasite replacement

Ore Textures of the Zone of Intense Recrystallization:

1. Textures related to nucleation
   - budding

2. Textures related to primary recrystallization
   - fine mosaic texture
3. Textures related to normal growth
   - equidimensional foam texture
4. Textures related to secondary recrystallisation
   sphalerite stars
   coarse crystal aggregates

Ore Textures related to detrital sedimentary processes and diagenesis:

1. Textures formed by transportation and deposition from traction currents:
   - Abrasion and rounding of particles
   - Sorting (Degree of maturity)
   - Lamination
   - Compaction and pressure solution
2. Textures related to diagenesis of detrital ore
   - Cementation
     - by spary calcite or dolomite
     - by overgrowth
     - by encrustations (Pisolithic crusts)
     - by poikilotopic cementation
     - by pore and fracture-filling with sparite or ore
   - Replacement or displacement
   - Deformation

3.5 The S-65 Metal and Metal Ratio Distributions

Introduction

The following is a discussion of computer generated, geochemical contour maps. Contoured are lead, zinc, iron and various ratios of the same. The assays were produced from chip samples collected during the drilling of the blast holes. The samples were analyzed in the mine laboratories of Pine Point Mines Ltd. using atomic absorption procedures. The assays are used by the geology department of Pine Point Mines Ltd. to control the grades during pit excavation and to produce stockpiles with predictable ore grades. Galena, sphalerite and marcasite crystal or grain sizes and other ore textures are, mostly for time reasons, not included in the grade control routine. By investigating the metal and metal ratio maps, the author intended to study trends in metal distribution which might be correlated with the host rock maps and ore textures of the S-65 ore body. To present the metal and metal ratio distribution in the S-65 deposit, the values from blast-hole analyses were plotted and contoured using the Surface II (FORTRAN Version) contouring package (Sampson, 1978,).

The Pb+Zn% Distribution Maps (Fig.3.5.I A,B and C)

In particular, the 1.0%, 5.0% and the 10.0% Pb+Zn contour lines delineate trends within the S-65 ore body. On

all three benches of S-65 the 1.0% Pb+Zn contour line shows approximately oval shaped areas with long axes at 30° azimuth. The long axes of the ovals are approximately 100 m and the perpendicular short axes approximately 70 m long.

Highs and Lows

On the first bench five ore zones with more than 10% Pb+Zn can be identified and will be referred to as the N, E-central, S and W ore zones. A small zone between the E-central and S-ore zones will be referred to as the SE-ore zone. The ore zones occur within a cross shaped area of the 5 to 10% Pb+Zn contour lines. In the SW quadrant of this cross is a low grade area (Fig.3.5.I A).

On the second bench the N and E central ore zones are substantially increased in size, while the W- ore zone has decreased in size. The small SE-ore zone disappears on the second bench, leaving the S-ore zone isolated. The SW-low is unchanged.

On the third bench the ore zones with more than 10% Pb+Zn are reduced to one central ore zone. A low in this ore zone was identified during pit mapping as a bottom high on the paleocave floor consisting of dolomitized J-facies.

The contoured area between 5 to 10% still extends to the west. The S-ore zone remains isolated. The SW-low is only faintly visible.

Lateral Extensions

Bulging or indenting of the oval outline indicates extension or recession of mineralization and solution activity. These lateral extensions represent either non-continuous, passive wings of the ore body or continuous, active solution channels, possibly connecting the breccia zone with a channel network of the South Trend. To avoid genetic implications at this point, the term lateral extensions is applied to these peripheral features; the origin of these extensions is discussed further in the text. The method of mining is such that the diameter of the excavation decreases with depth. In the case of a cylindrical breccia zone this procedure may lead to erroneous interpretations regarding karst activity because less surface area is exposed for study as mining advances onto lower benches.

On the first bench lateral extensions are indicated by a weak bulging of the 1.0% contour line at 20°, 90°, 190° and 290° azimuth. The four above mentioned larger than 10.0% Pb+Zn ore zones occur directly inward from these lateral extensions forming a cross shape with a low in the SW quadrant.

On the second bench, the combined ore distribution map shows lateral extensions protruding further outward compared to those on the first bench. Lateral extensions are more prominent at the 20° and the 290° locations. Less clear

are the lateral extensions towards the east and south. The southern extension seems to widen or to split up into three. On the third bench the low at 230° azimuth is only faintly visible and the S-ore zone occurs now in the breccia zone between the 230° and 190° lateral extensions. The N and W-ore zones are completely joined and occur in between the possibly related lateral extensions at 20° and 290°. Weakly indicated is also a new lateral extension to the E at 90°.

The Sinkhole

On all three benches of S-65, the sinkhole coincides with the S-lateral extension and the S-ore zone (more than 5% Pb+Zn). The economic grades of the sinkhole were only recorded on the geological map of the third bench (Fig.3.3.IV A,B,C). However, the Pb%+Zn% distribution maps of the first and second benches indicate grades above 5% as well. Possibly this type of ore was not recognized.

The SW-low and generally low Pb%+Zn% values form a halo around the sinkhole. The following process could be a possible genetic process explaining the ore distribution:

1.Ore deposition at the south end of S-65, possibly related to the S-lateral extension.

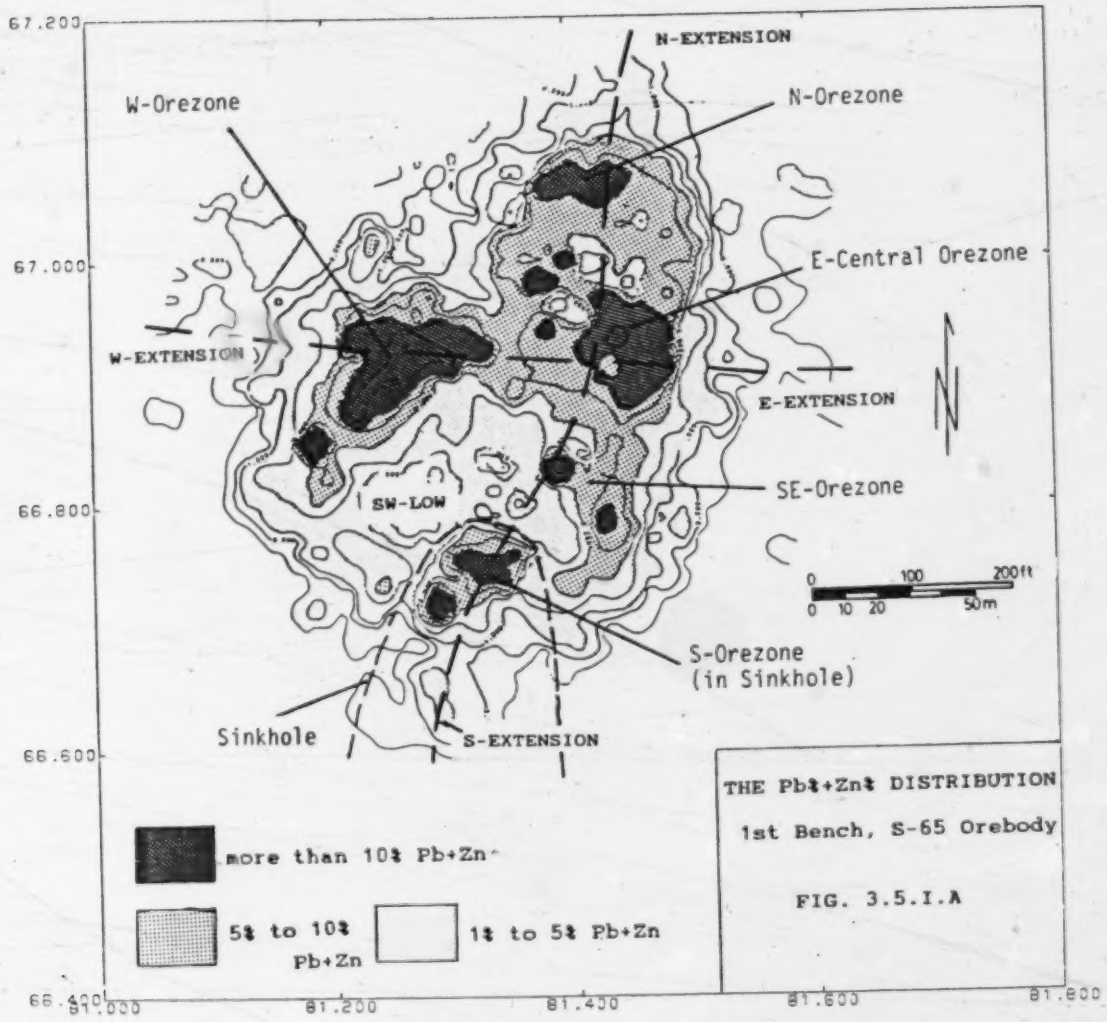
2.Dissolution and removal of the S-ore zone leaving a cavity.

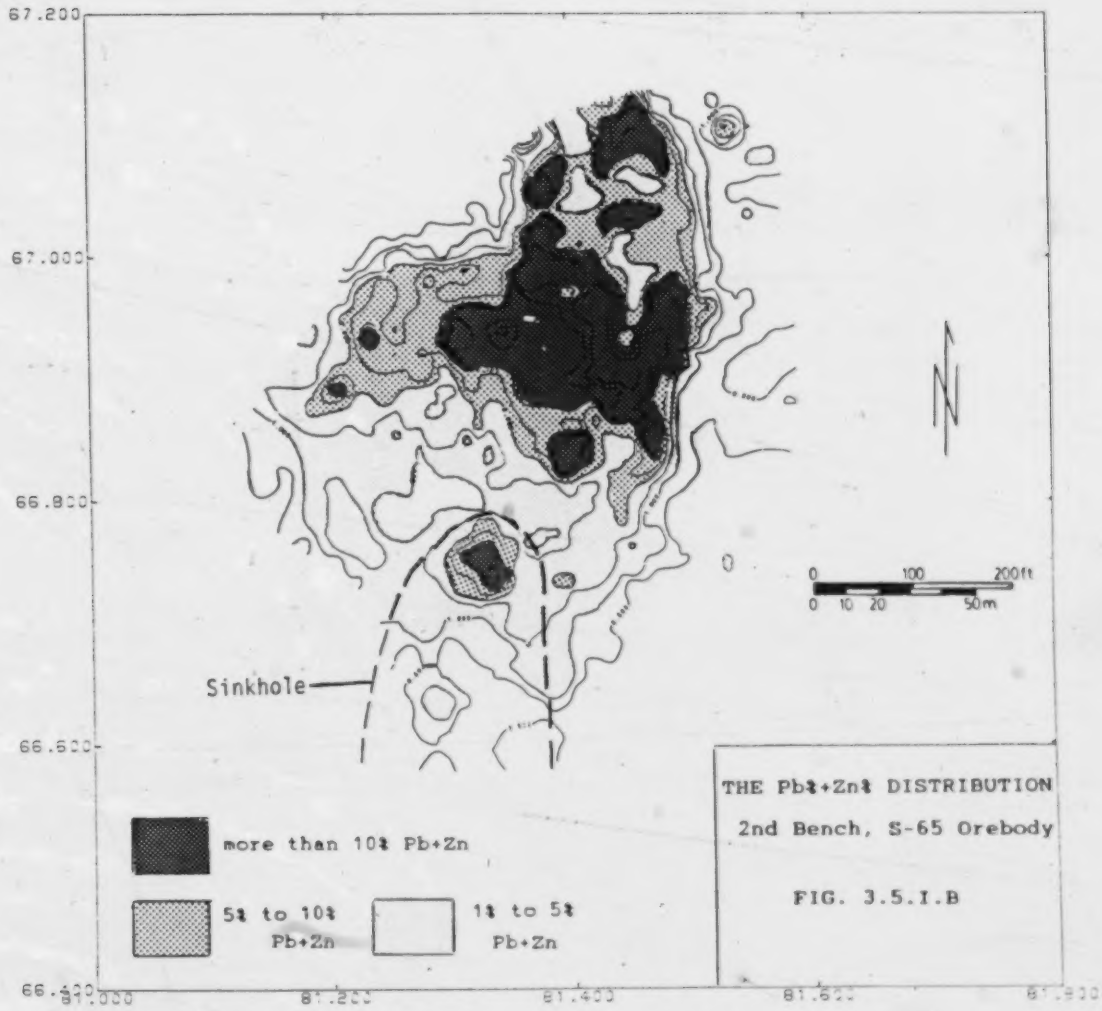
3.Infill of the cavity with Pleistocene material mixed with mechanically transported sulfides

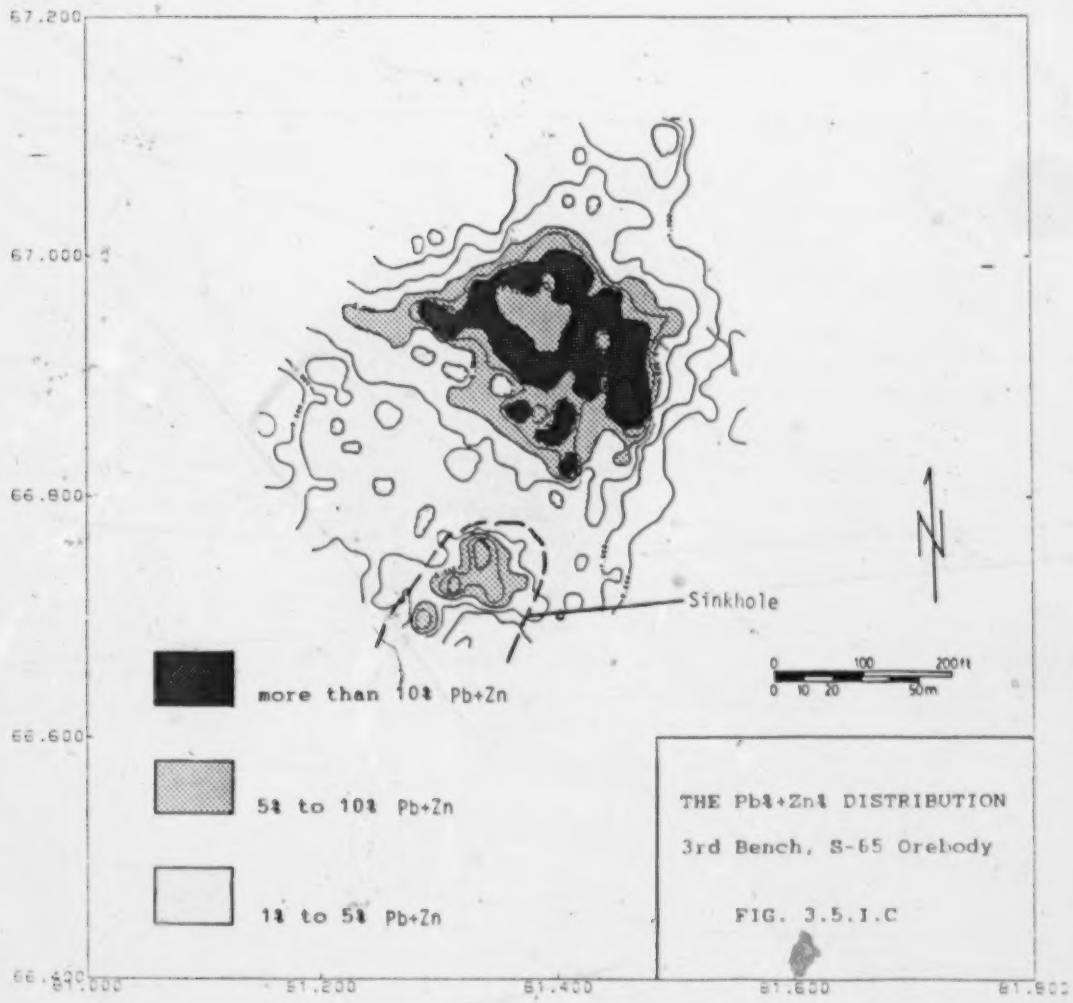
from adjacent ore zones (See under Ore Textures of the Sinkhole).

4.The mechanical removal of the adjacent ore creates the SW-low around the sinkhole.

This theory of mechanically derived ore from immediate surroundings is supported by the Pb/Zn ratio of 1/5 which is a characteristic average for the entire S-65 ore body.


67.200
67.000
66.800
66.600
66.400
81.000
81.200
81.400
81.600
81.800
N-EXTENSION
N-Orezone
W-Orezone
E-Central Orezone
W-EXTENSION
E-EXTENSION
SE-Orezone
SW-LOW
S-Orezone
(in Sinkhole)
Sinkhole
S-EXTENSION
0 100 200ft
0 10 20 50m
more than 10% Pb+Zn
5% to 10% Pb+Zn
1% to 5% Pb+Zn
THE Pb%+Zn% DISTRIBUTION
1st Bench, S-65 Orebody
FIG. 3.5.I.A


67.200
67.000
66.800
66.600
66.400
81.000
81.200
81.400
81.600
81.800
Sinkhole
0 100 200ft
0 10 20 50m
more than 10% Pb+Zn
5% to 10% Pb+Zn
1% to 5% Pb+Zn
THE Pb%+Zn% DISTRIBUTION
2nd Bench, S-65 Orebody
FIG. 3.5.I.B


67.200
67.000
66.800
66.600
66.400
61.000
61.200
61.400
61.600
61.800
Sinkhole
N
0 100 200ft
0 10 20 50m
more than 10% Pb+Zn
5% to 10% Pb+Zn
1% to 5% Pb+Zn
THE Pb%+Zn% DISTRIBUTION
3rd Bench, S-65 Orebody
FIG. 3.5.I.C

The Pb% Distribution Maps (Fig.3.5.II A,B and C)

The plotting of combined Pb%+Zn% values is mainly of mining interest. The minerals galena and sphalerite, however, are concentrated at specific and differing locations. For these reasons the combined ore distribution is discussed followed by a discussion of the Pb% and Zn% distribution maps separately.

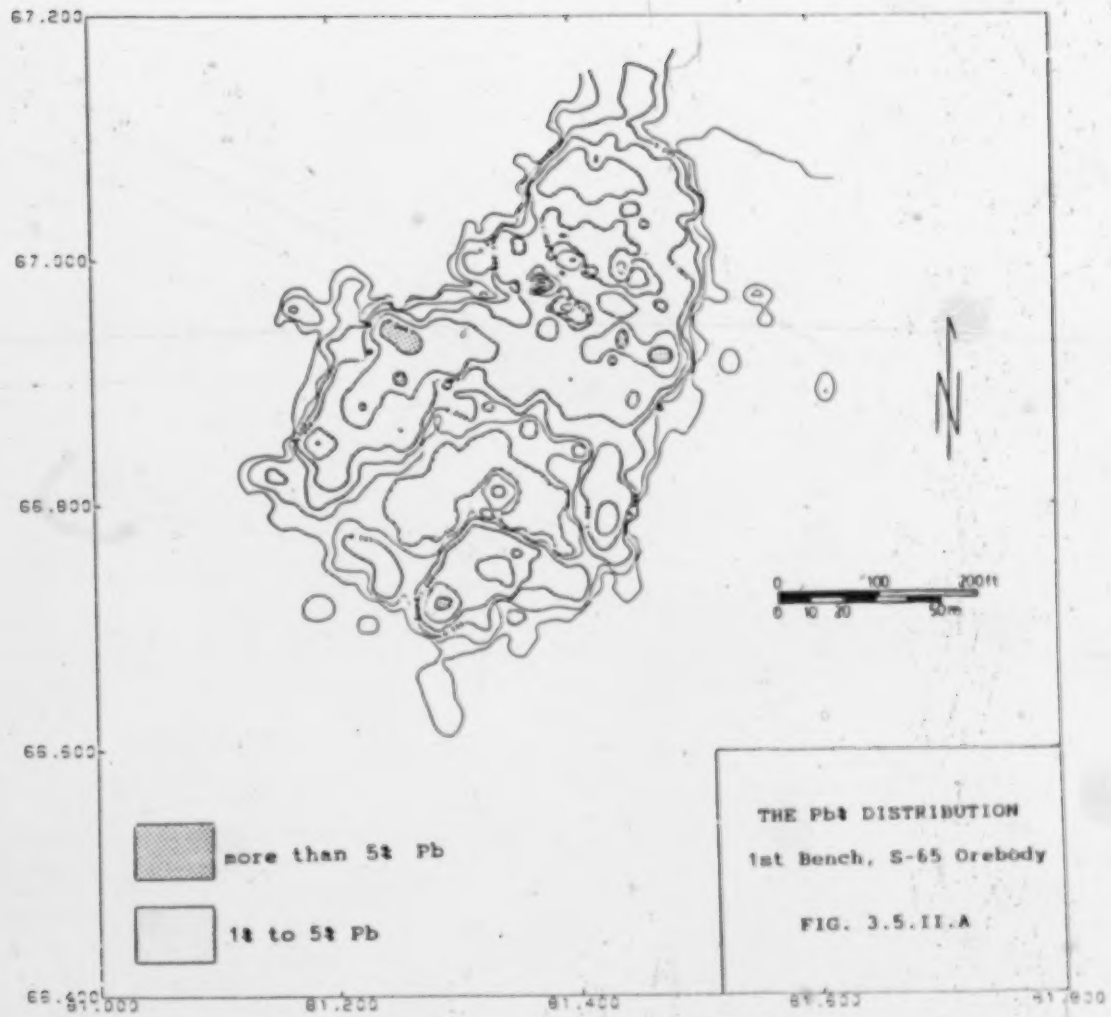
The following observations from previous chapters pertinent to the distribution of galena should be recalled: The ore grades of the S-65 ore body averaged 1.2 Pb% and 5.7 Zn%. For the purpose of this thesis a ratio of Pb/Zn = 1/5 will be used. The study of the ore textures showed that galena after initial growth is not mobile and the only change is caused by in situ recrystallization. Therefore, the Pb% distribution maps will provide information about early stage ore formation. An exception is the detrital ore of the sinkhole which was abraded and mechanically transported from adjacent rock portions maintaining a constant Pb/Zn ratio of 1/5.

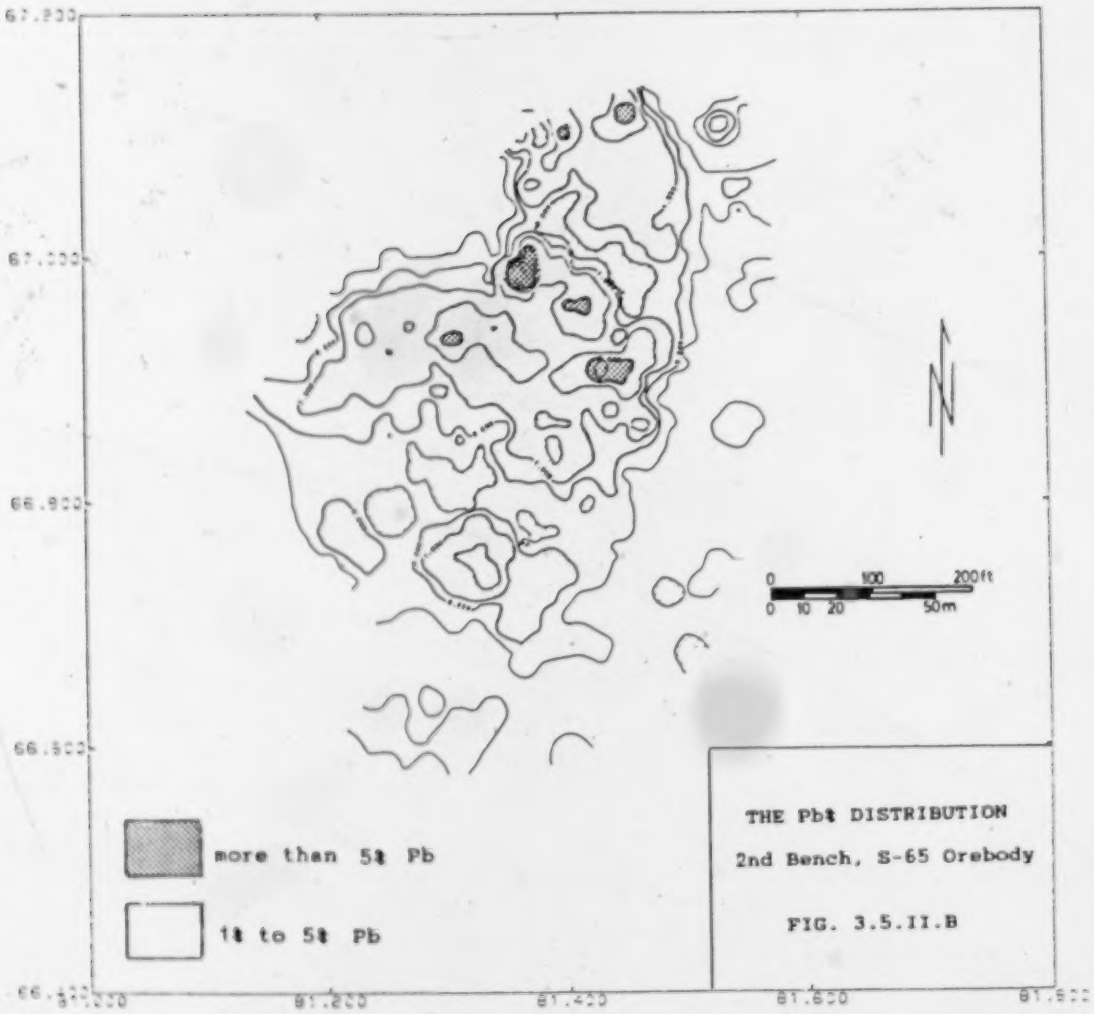
It is immediately obvious upon comparison of the Pb% maps with the combined ore map that the Pb% ore is restricted to smaller areas within the combined ore zones. The 1.0% Pb contour lines are similar to the 5.0% contour lines of the Pb%+Zn% maps. This corresponds with overall 1/5 Pb/Zn ratio of the S-65 ore body. The 0.75% to 1.0% Pb contour lines are equally and closely spaced on maps on all

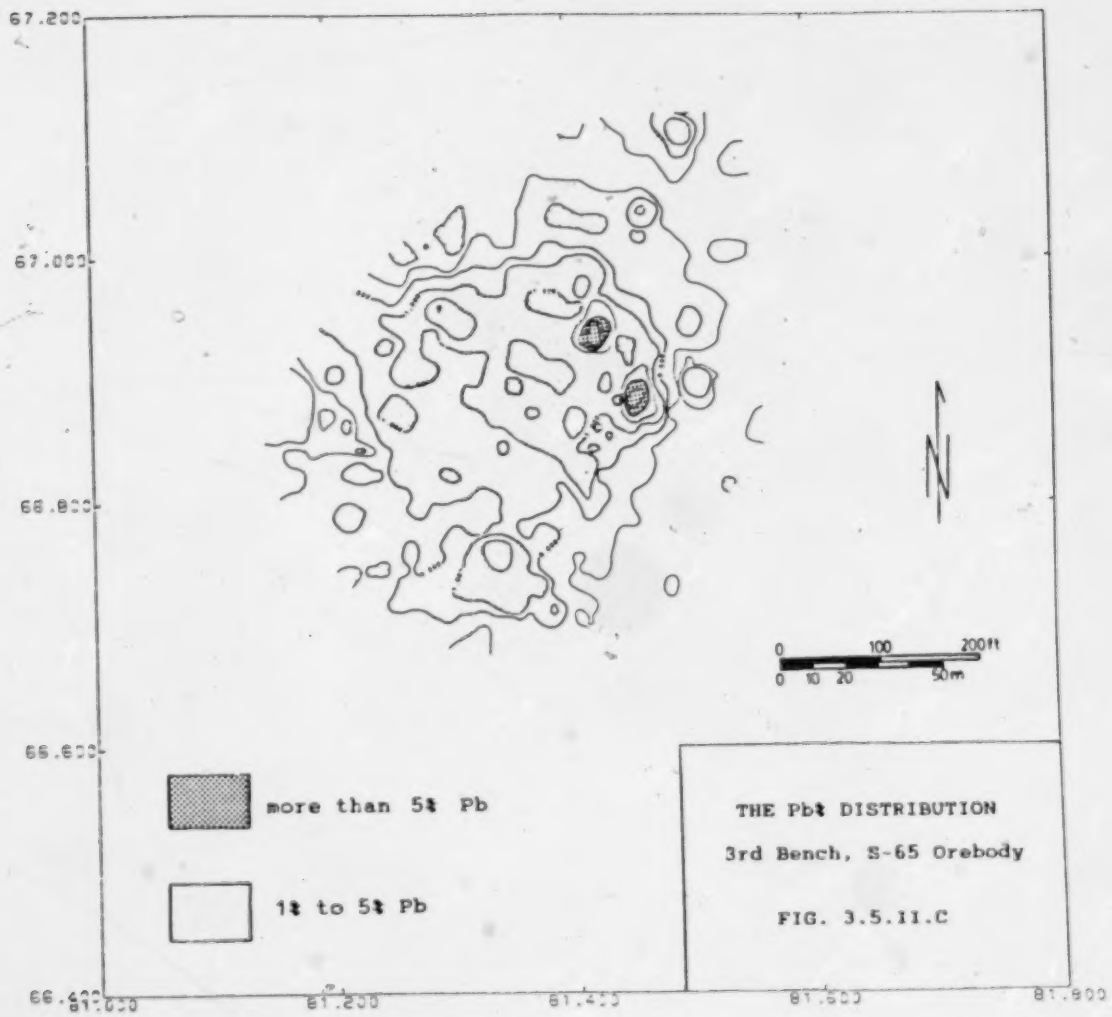
benches in pit S-65. The contour spacing from 0.25 to 0.5% Pb is wider and more irregular. The contour lines above 1.0% are also widely spaced. Only a few zones with values larger than 5.0% Pb were outlined. This trend in values indicates that after a very gradual increase of Pb% background values a rapid increase to approximately 1.0% Pb occurs. There are only minor deviations on the 1.0% Pb plateau.

Lateral extensions are, with the exception of the N-extension, less visible on the Pb% map than on the combined Pb+Zn% map. The N-extension at 20° azimuth appears on the first and second benches but narrows down on the third bench. The SW and W-lateral extensions at 190° and 290° azimuth respectively, are not visible on the first bench but become obvious on the second and third benches. The low grade zone in the SW-part of the oval shaped breccia zone is visible and laterally extensive on the first bench but it is almost non-existent by the third bench. The E-linear ore zone is obvious only on the first mining level. Pb% values do not occur beyond the eastern boundary of the oval breccia zone.

It can be concluded that a 1% Pb contour line contours the outline of the breccia ore of early sulfide deposition. On the 2nd bench this mineralizing process seems to be connected with the W and N-lateral extensions.


67.200
67.000
66.800
66.600
66.400
81.000
81.200
81.400
81.600
81.800
0 100 200ft
0 10 20 50m
more than 5% Pb
1% to 5% Pb
THE Pb% DISTRIBUTION
1st Bench, S-65 Orebody
FIG. 3.5.II.A

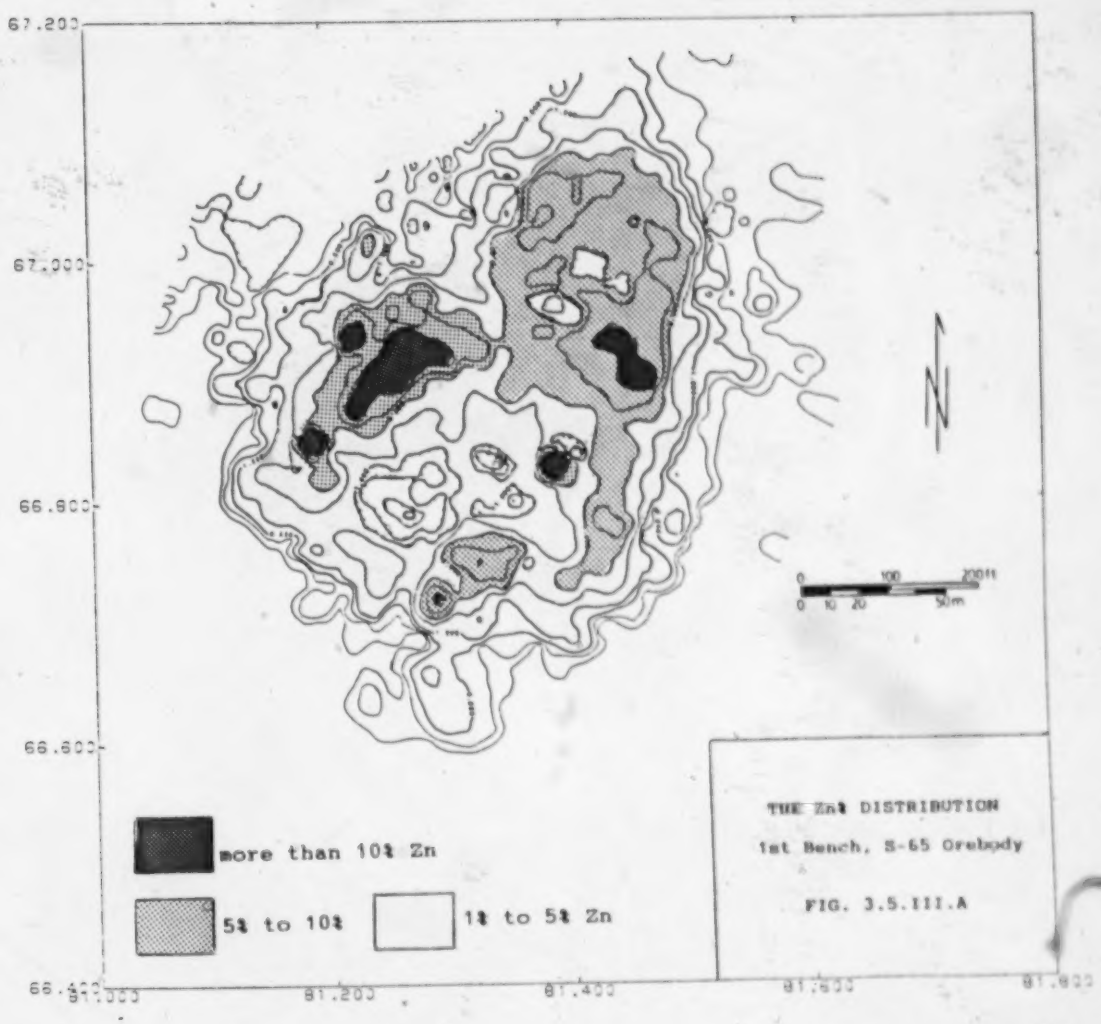

67.800
67.000
66.800
66.600
81.000
81.200
81.400
81.600
81.800
0 100 200ft
0 10 20 50m
more than 5% Pb
1% to 5% Pb
THE Pb% DISTRIBUTION
2nd Bench, S-65 Orebody
FIG. 3.5.II.B

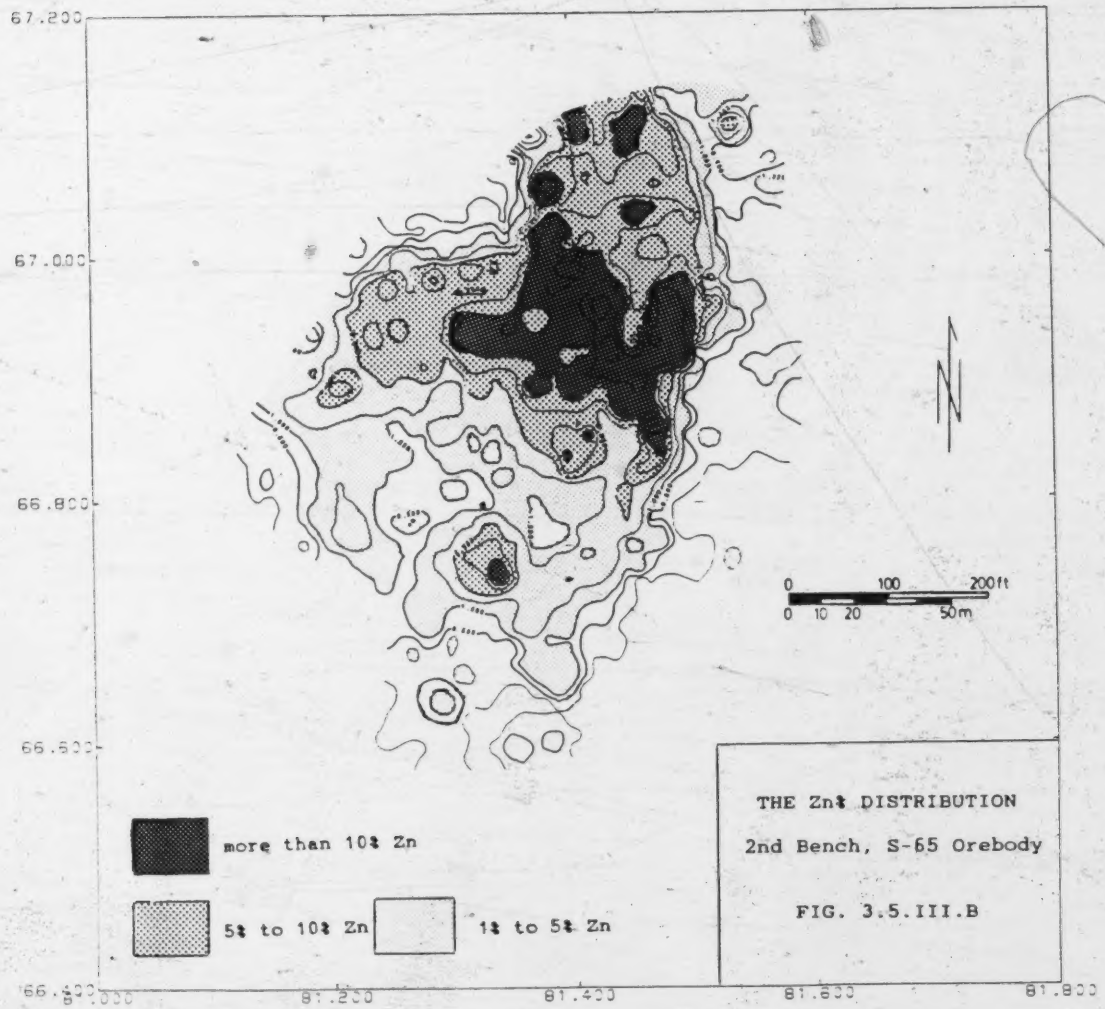

67.200
67.000
66.800
66.600
66.400
81.000
81.200
81.400
81.600
81.800
0 100 200ft
0 10 20 50m
more than 5% Pb
1% to 5% Pb
THE Pb% DISTRIBUTION
3rd Bench, S-65 Orebody
FIG. 3.5.11.C

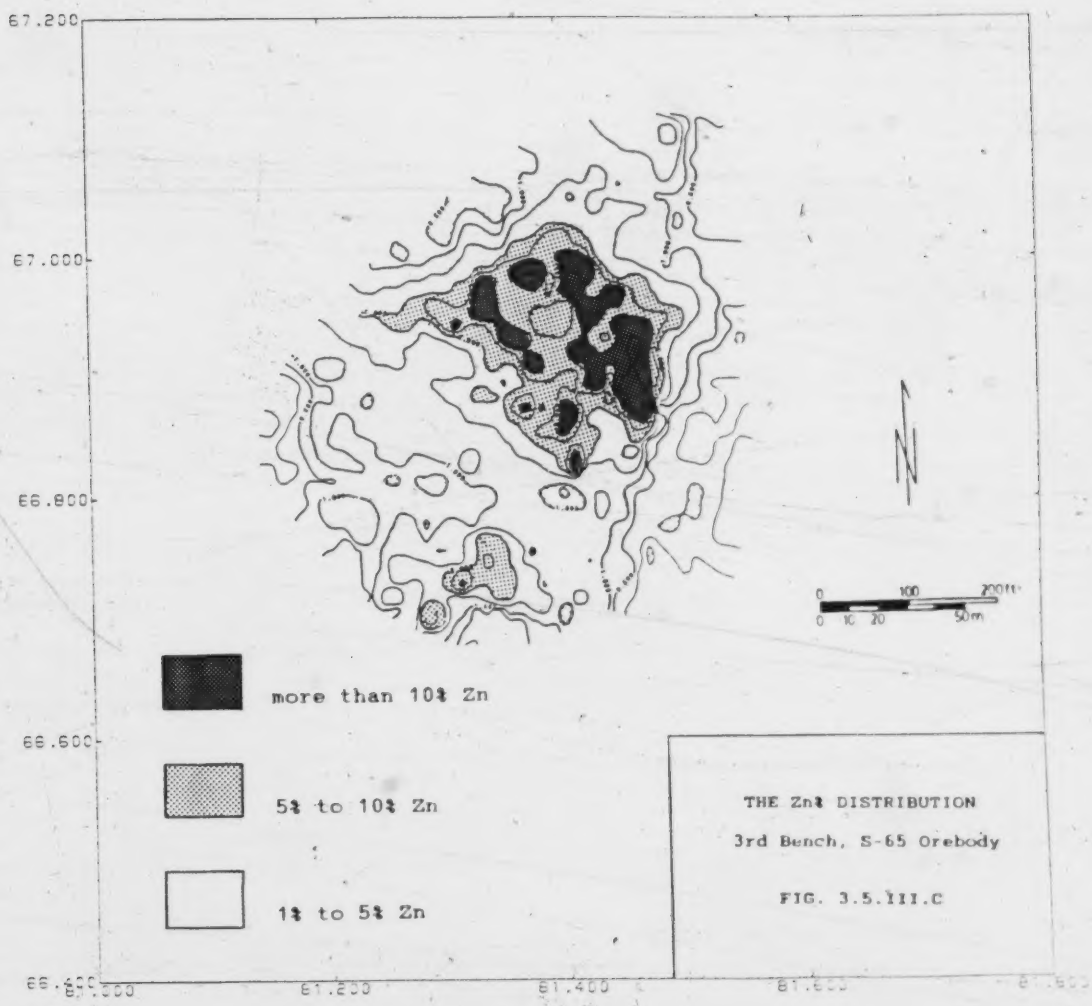
The Zn% Distribution Maps (Fig.3.5.III A,B and C)

The uniform, plateau like distribution of galena causes a striking similarity between the Pb+Zn% distribution and the Zn% distribution. Highs, lows and lateral extensions of the Zn% maps are virtually identical to those of the Pb+Zn% maps. The Zn% is generally higher than the Pb%, and the area outlined by the 0.5% and 1.0% Zn contour lines is considerably larger. The Zn% contours do not indicate a plateau at a certain grade. The greater variety in contoured features, especially in lateral extensions, corresponds with a greater variety in sphalerite textures. This is likely indicative of a greater mobility of sphalerite. Noticeable is a constant, gradual change from background to high grade Zn% shown by the constant contour spacing. Only at the eastern limit of the breccia zone are the contour lines more closely spaced. The transition from unaltered host rock to high grade ore is especially rapid in this area. On the third bench this steep gradient is interrupted by outwardly bulging contour lines, which indicate a lateral extension. A zone of greater than 10.0% Zn is recognized near this extension.

The SW-low grade zone shows up clearly on all pit levels. The S-ore zone at 190° azimuth is relatively small and decreases in size towards the third bench.


67.200
67.000
66.800
66.600
66.400
81.000
81.200
81.400
81.600
81.800
0 100 200m
0 10 20 50m
more than 10% Zn
5% to 10%
1% to 5% Zn
THE Zn% DISTRIBUTION
1st Bench, S-65 Orebody
FIG. 3.5.III.A


67.200
67.000
66.800
66.600
66.400
81.000
81.200
81.400
81.600
81.800
0 100 200ft
0 10 20 50m
more than 10% Zn
5% to 10% Zn
1% to 5% Zn
THE Zn% DISTRIBUTION
2nd Bench, S-65 Orebody
FIG. 3.5.III.B


67.200
67.000
66.800
66.600
66.400
more than 10% Zn
5% to 10% Zn
1% to 5% Zn
THE Zn% DISTRIBUTION
3rd Bench, S-65 Orebody
FIG. 3.5.III.C

The $\frac{Pb\%}{Zn\%}$ Distribution Maps (Fig.3.5.IV A,B and C)

A comparison of the separate Pb% and Zn% distribution maps can be made using the Pb/Zn distribution maps.

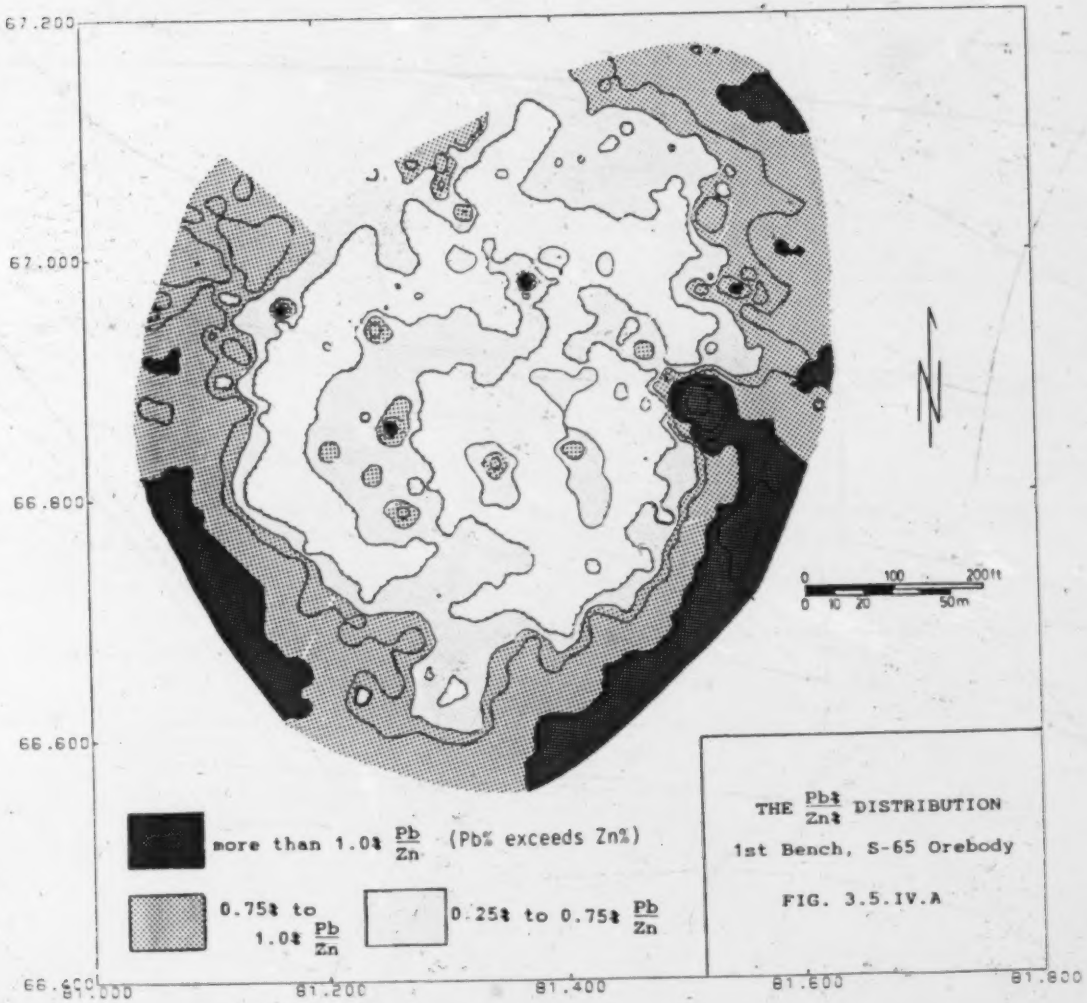
The mineralized area of the first bench is outlined by a constant plateau of the Pb/Zn 0.25% contour line. This plateau has an oval outline similar to that of the mapped breccia zone. The N, E central, S and W ore zones do not show on this plot. The SW-low on the Pb%+Zn% map is not identifiable on the Pb/Zn plot. The Pb/Zn ratio on this bench is therefore constant throughout high and low grade ore zones at values below 0.75% Pb/Zn. No lateral extensions can be identified on this bench.

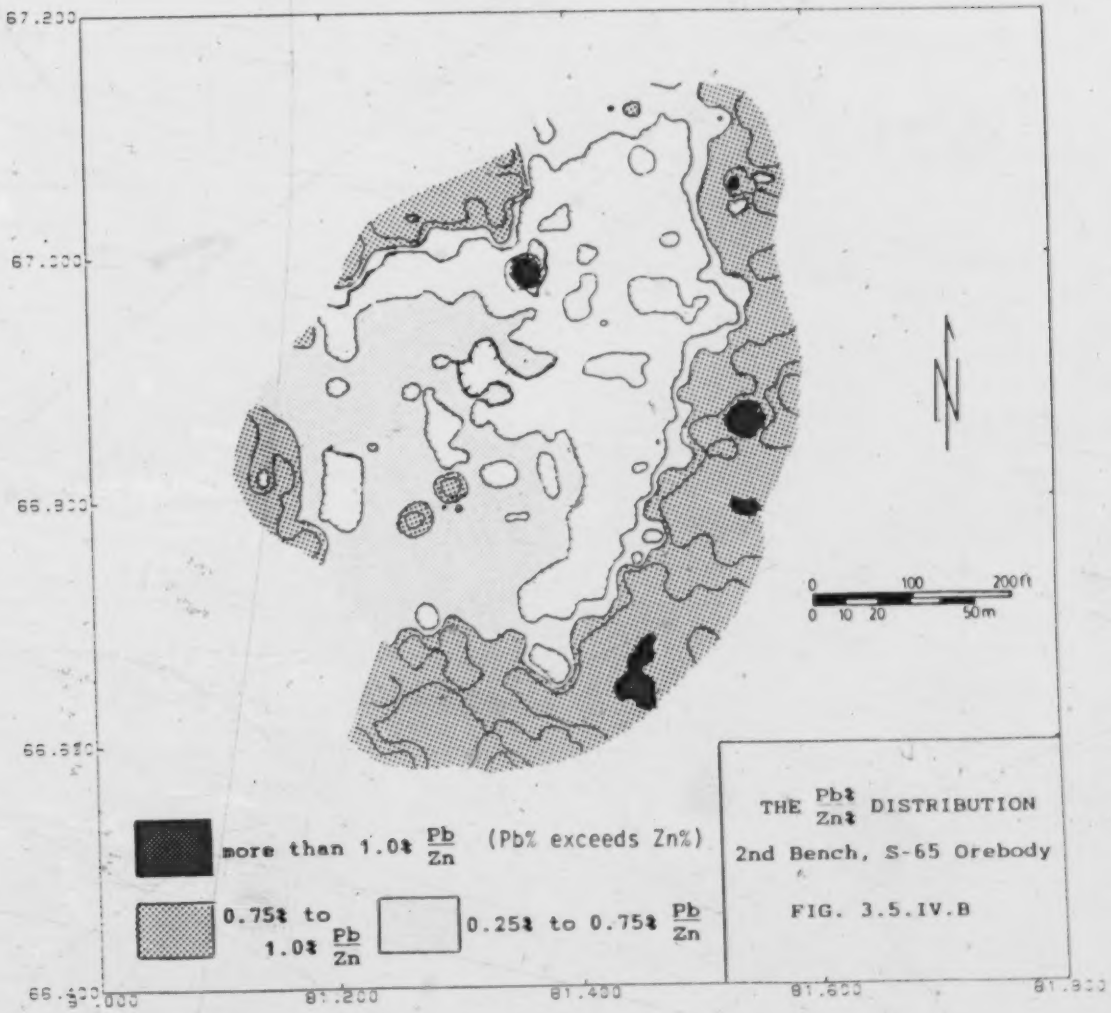
On the second bench a Pb/Zn low, i.e. a relative Zn% increase, occurs along the northern and eastern outer edge of the ore body displaying approximately the cross shaped area observed on the Pb%+Zn% map. The main zone of relative Zn% increase is found in the E central ore zone. A marked relative increase in Pb% occurs in the SW-low. A Pb% increase marks the location of the E-lateral extension.

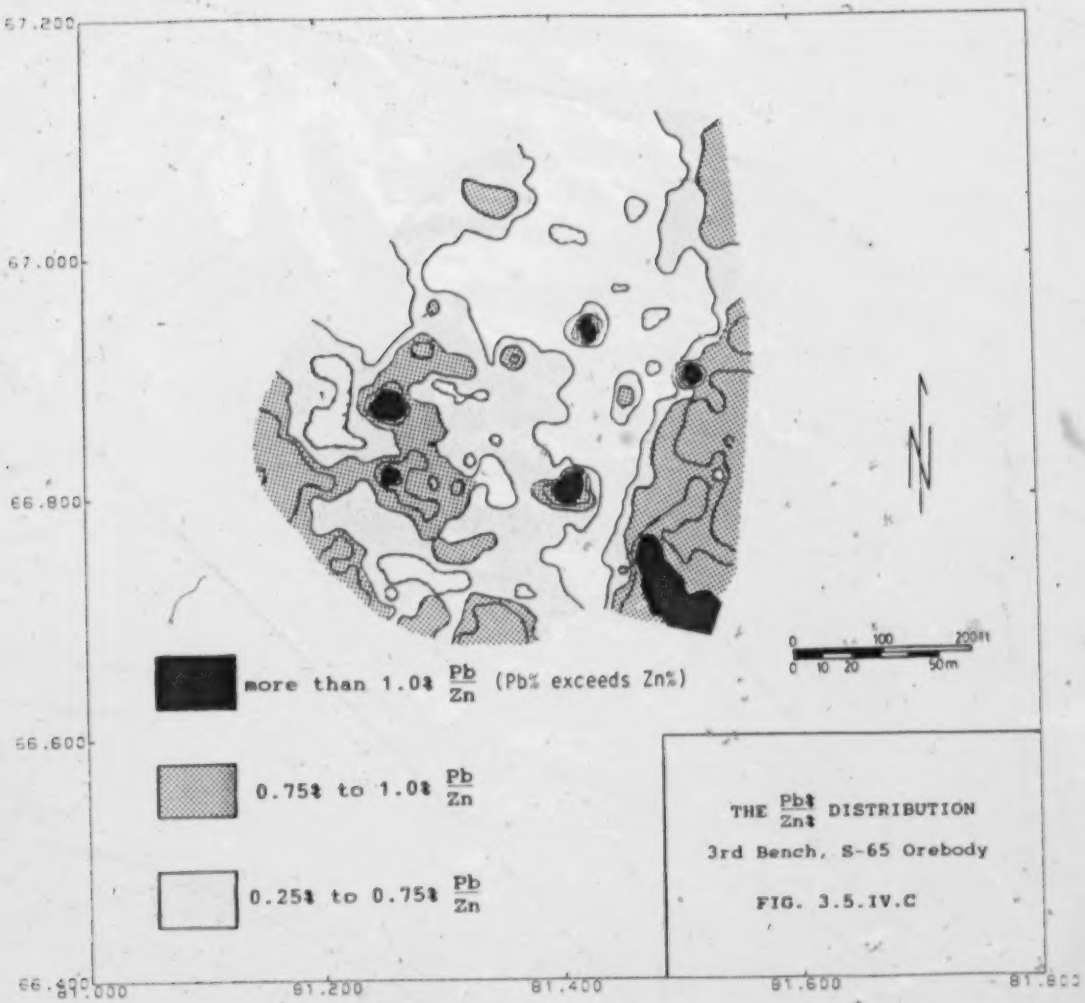
The trend observed on the second bench becomes even more pronounced on the third bench. Pb% increases relative to Zn% in the SW quadrant at the location of the SW-low. The S lateral extension is indicated by a relative Zn% increase. A large area of relative Zn% enrichment occurs in the northeast quadrant where it actually merges into the

N-lateral extension. The W-lateral extension is less pronounced.

It can be concluded that the Pb/Zn maps do not show the high and low grade ore zones. However, the lateral extensions appear as increases in the relative Zn content. This association of Zn with lateral extensions can be explained by a greater mobility of zinc.


67.200
67.000
66.800
66.600
66.600
81.000
81.200
81.400
81.600
81.800
0 100 200ft
0 10 20 50m
more than 1.0% Pb/Zn (Pb% exceeds Zn%)
0.75% to 1.0% Pb/Zn
0.25% to 0.75% Pb/Zn
THE Pb%/Zn% DISTRIBUTION
1st Bench, S-65 Orebody
FIG. 3.5.IV.A


67.200
67.000
66.800
66.600
66.400
81.000
81.200
81.400
81.600
81.800
0 100 200ft
0 10 20 50m
more than 1.0% Pb/Zn (Pb% exceeds Zn%)
0.75% to 1.0% Pb/Zn
0.25% to 0.75% Pb/Zn
THE Pb%/Zn% DISTRIBUTION
2nd Bench, S-65 Orebody
FIG. 3.5.IV.B


67.200
67.000
66.800
66.600
66.400
81.000
81.200
81.400
81.600
more than 1.0% Pb/Zn (Pb% exceeds Zn%)
0.75% to 1.0% Pb/Zn
0.25% to 0.75% Pb/Zn
0 100 200ft
0 10 20 50m
THE Pb%/Zn% DISTRIBUTION
3rd Bench, S-65 Orebody
FIG. 3.5.IV.C

The Fe% Distribution Maps (Fig.3.5.V A,B and C)

It is immediately evident upon visual inspection of the distribution maps that there are almost no similarities between the Pb% or Zn% and Fe% distribution. On the first and second benches the oval outline of the mineralized breccia zone is still visible. However, the pit excavation on the third bench did not extend laterally far enough to encounter the outer limit of the marcasite occurrences. It appears on regional exploration maps that a slight marcasite enrichment envelopes the whole ore body.

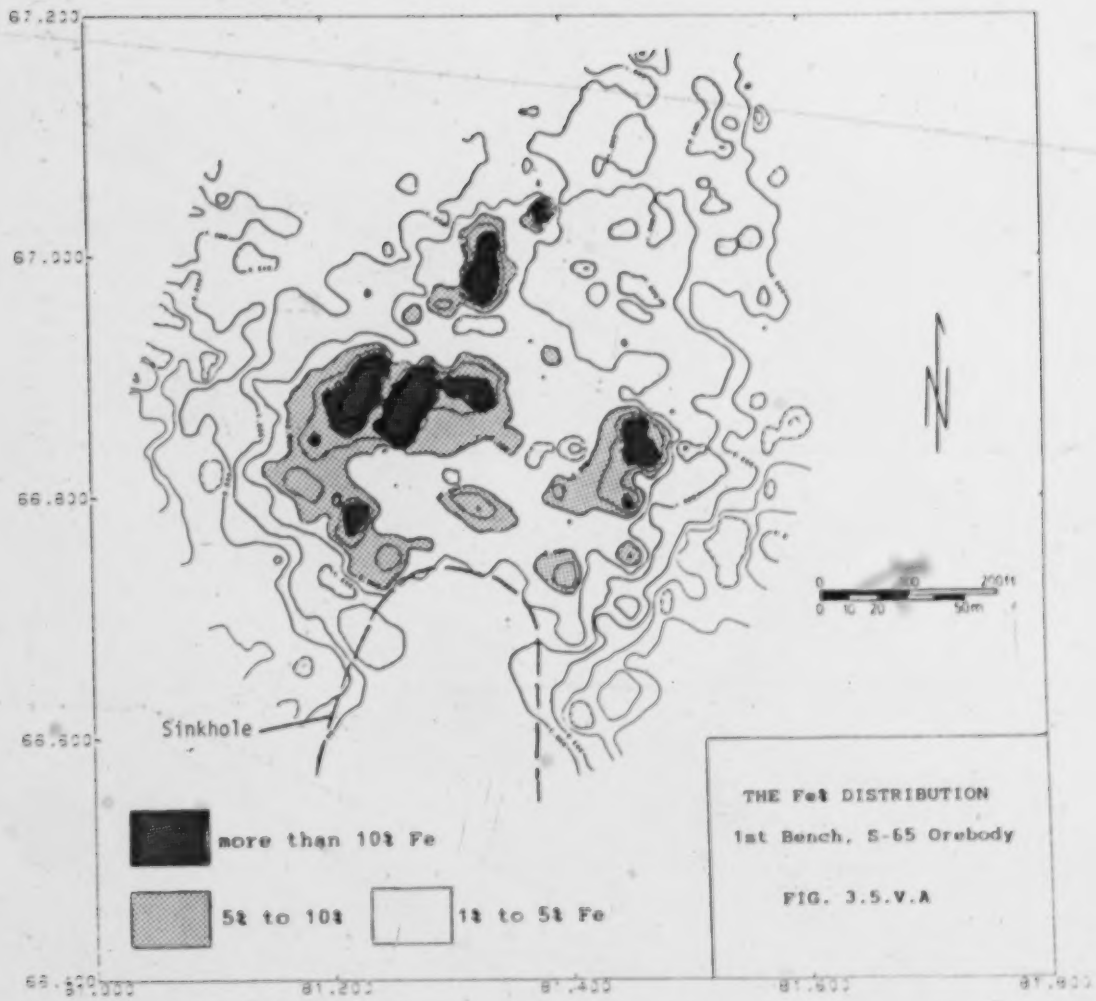
On the first bench the 0.5 and 1.0% Fe contours show broad widening at the N, W and S-lateral extensions. The increase of Fe% at the N-lateral extension has shifted slightly to the west in comparison to its location on the previous maps. Only two of the Fe% zones larger than 5.0 and 10.0% Fe correspond with highs of the Pb%+Zn% distribution maps: The W-ore zone and the small SE-ore zone have on the first bench also high Fe% values. The SW low grade zone so closely surrounded by increased Fe values that it is only poorly recognizable. The S, N and E-central ore zones are not reflected in any increased marcasite occurrences.

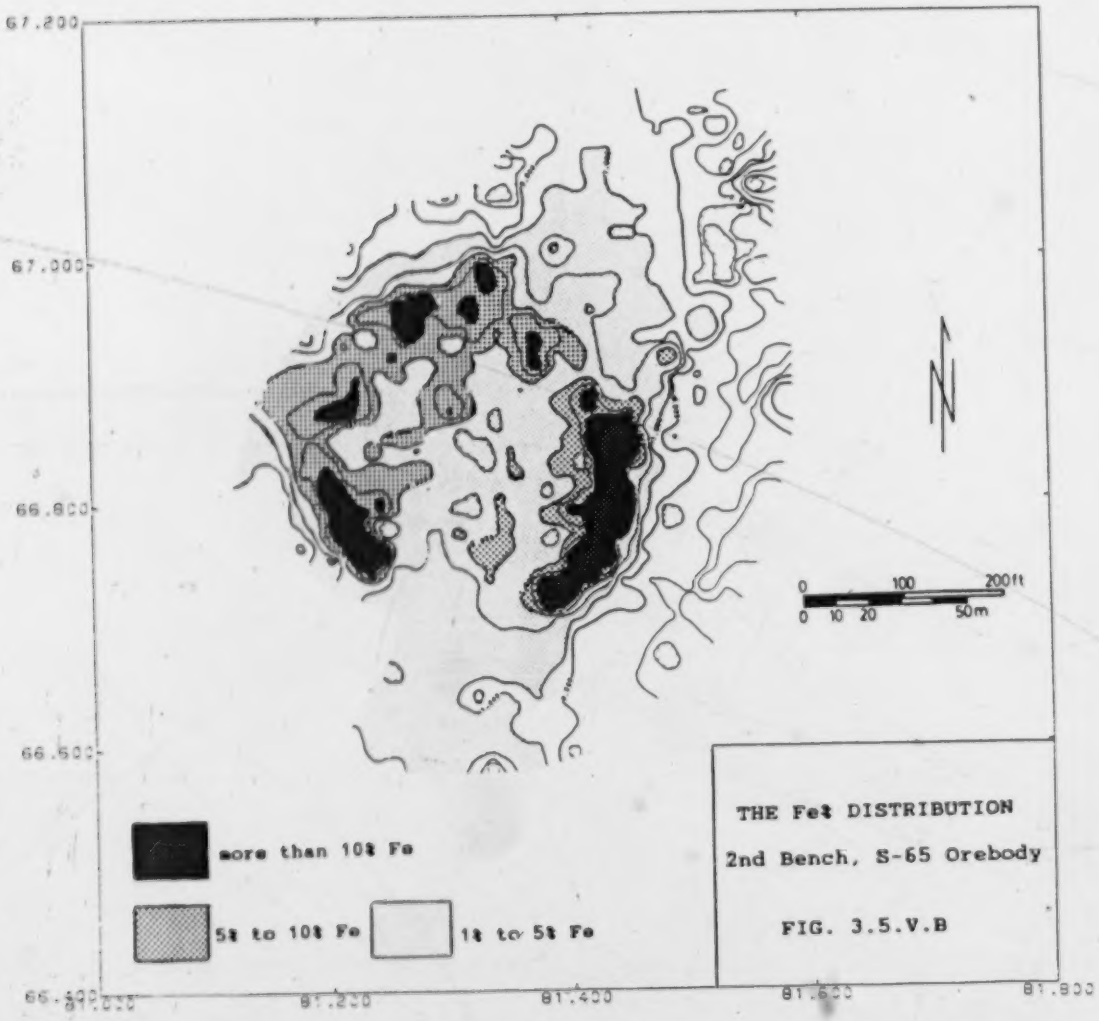
On the second bench, larger than 5.0% Fe concentrations form a rim around the SW-low and the S-ore zone. This rim overprints and increases the Fe content of the W and SE-ore zones. Otherwise the Fe% concentration seems to be unrelated to any ore concentration.

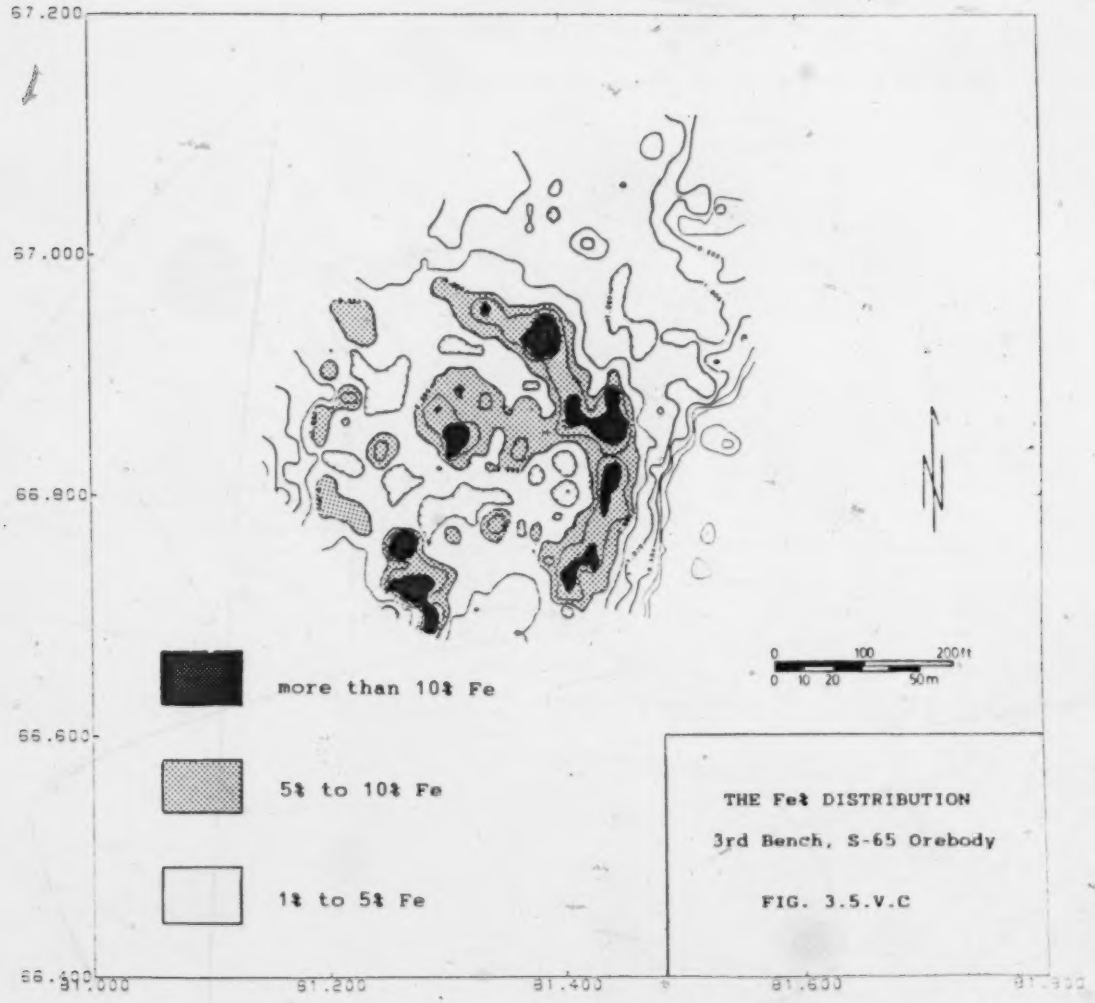
Remarkable are the high Fe% concentrations and the steep gradients in the rim where the mineralized breccia passes into unaltered host rock. 1% Fe values continue into the pit wall at the locations of the W and S-lateral extensions.

On the third bench, there is again no apparent correlation between Pb% or Zn% highs and Fe% highs. A Fe% rim occurs around the SW-low and S-ore zone. This Fe% rim is open to the south. The J-facies bottom high on the paleocave floor recognized during pit mapping showed low Zn% and Pb% concentrations. On the Fe% distribution map however, this feature corresponds to a 10.0% Fe high, connected with the Fe% rim to the south which encircles the SW-low and the S-ore zone.

It can be concluded that the Fe distribution is the result of late, overprinting processes. The Fe rim itself is related to the Pleistocene sinkhole which intruded the ore body from the south. The W and S-lateral extensions have, especially on the second bench, noticeably increased Fe% values.


67.200
67.000
66.800
66.600
66.400
81.000
81.200
81.400
81.600
81.800
Sinkhole
more than 10% Fe
5% to 10%
1% to 5% Fe
THE Fe% DISTRIBUTION
1st Bench, S-65 Orebody
FIG. 3.5.V.A


67.200
67.000
66.800
66.600
66.400
81.000
81.200
81.400
81.600
81.800
0 100 200ft
0 10 20 50m
more than 10% Fe
5% to 10% Fe
1% to 5% Fe
THE Fe% DISTRIBUTION
2nd Bench, S-65 Orebody
FIG. 3.5.V.B


67.200
67.000
66.800
66.600
66.400
more than 10% Fe
5% to 10% Fe
1% to 5% Fe
0 100 200ft
0 10 20 50m
THE Fe% DISTRIBUTION
3rd Bench, S-65 Orebody
FIG. 3.5.V.C

The $\frac{(Pb\%+Zn\%)}{Fe\%}$ Distribution Maps (Fig.3.5.VIII A,B,C)

The lead / zinc ore over iron ratio map provides a combination of the previously described maps.

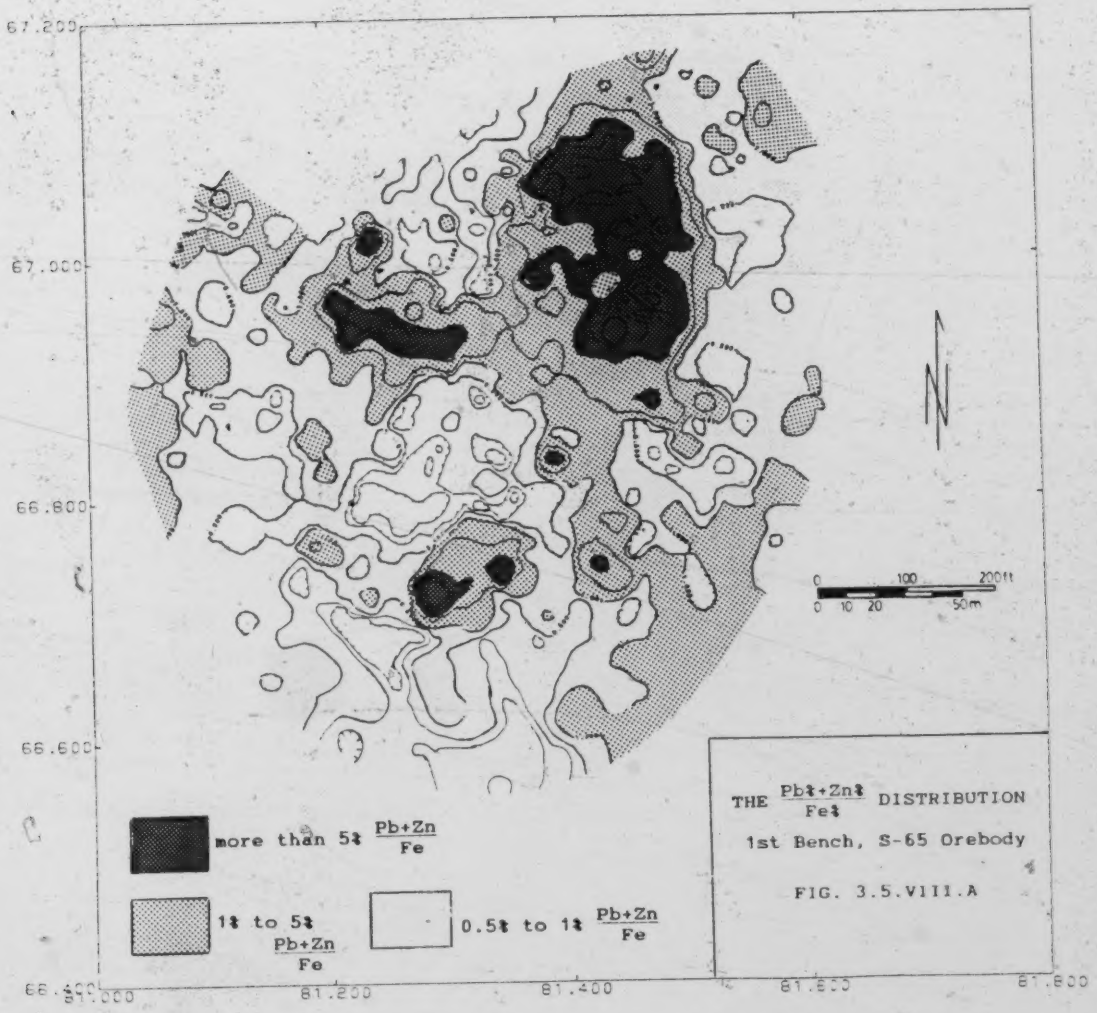
On all benches a similarity between this and the Pb+Zn maps is noticeable. This similarity can be understood through the study of ore textures. It was observed, that marcasite of later stages preferred to grow on top or replace sphalerite crystals. Secondary marcasite enrichment will therefore follow preexisting sphalerite enrichment. This explains that the J-facies bottom high in the E-central ore zone does not show on the ore over iron map: The secondary marcasite enrichment deposited more marcasite on sphalerite seeds and less in the bottom high. This kept the ore over iron ratio constant across the bottom high.

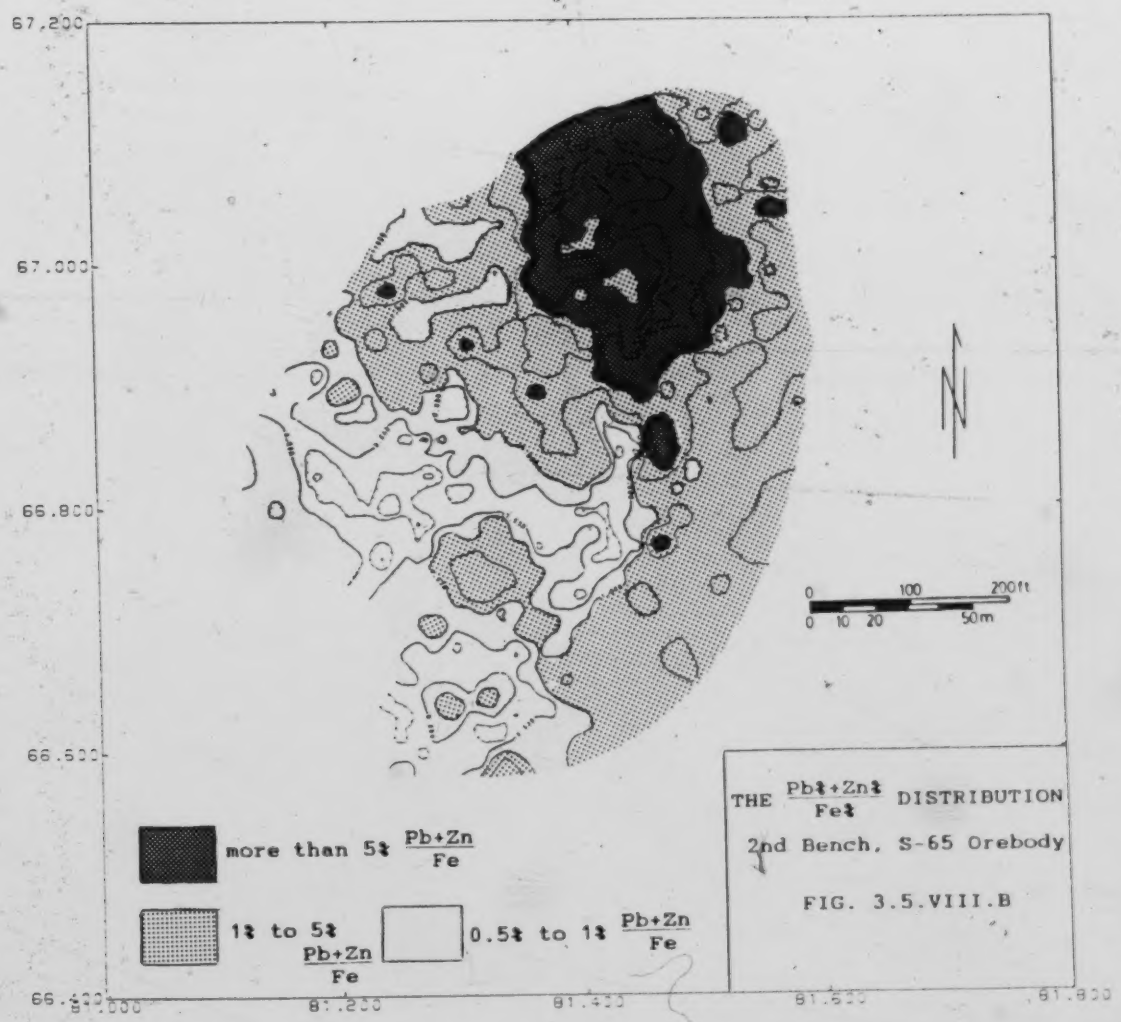
The marcasite halo around the SW-low and the S-ore zone corresponds to Pb and Zn depleted zones. It seems to have formed in a host rock from which galena and sphalerite were removed to fill the sinkhole.

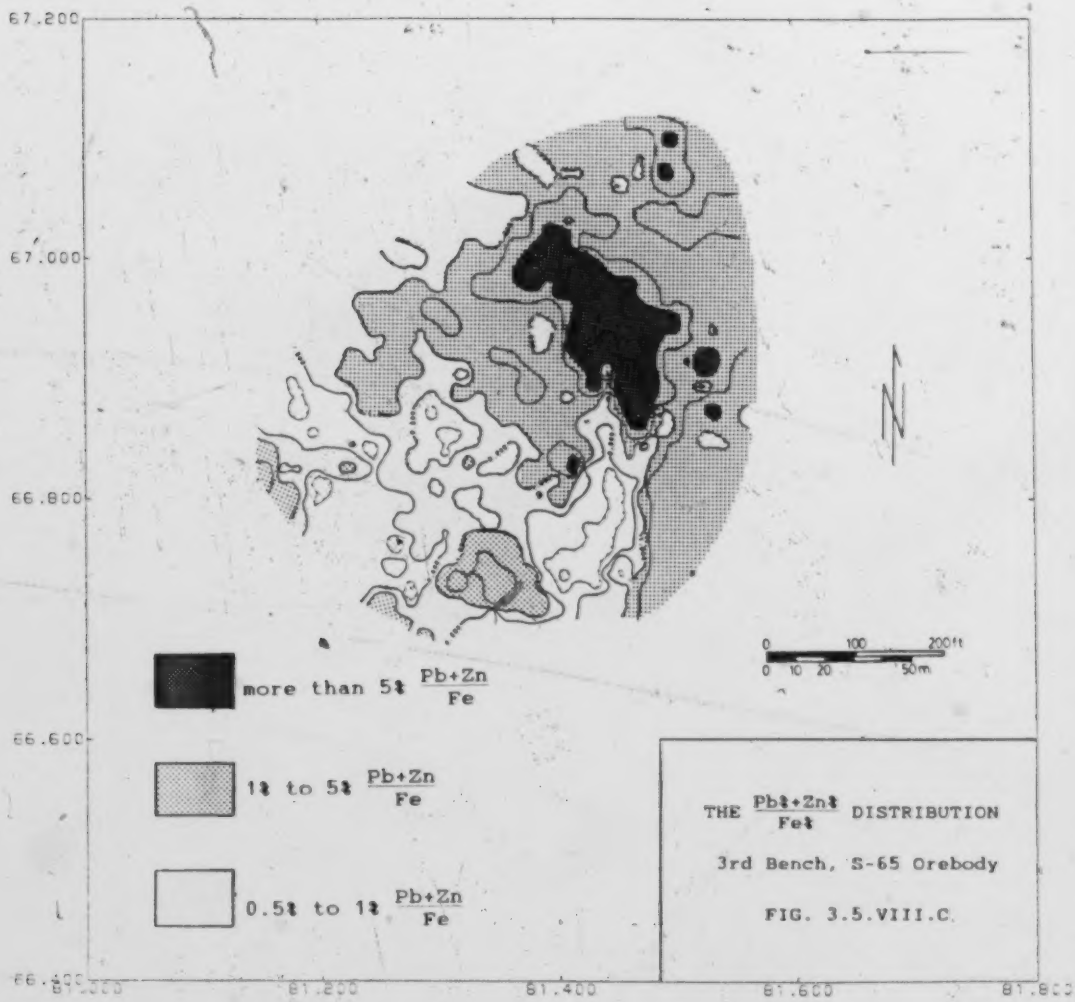
It appears, that the W- and S-lateral extensions and the entire SW-portion of the ore body are marcasite-rich. The N-lateral extension and the entire NE-portion of the ore body are galena- and sphalerite-rich. The relative Fe increase from the NE to the SW exceeds the pit limits and overpowers evidence of lateral extensions.

The Pb and Fe maps show that galena ore zones are clearly defined with sharp Fe increases beside the ore

highs. There seems to be a inverse relationship between galena and marcasite.


67.200
67.000
66.800
66.600
66.400
81.000
81.200
81.400
81.600
81.800
0 100 200ft
0 10 20 50m
more than 5% Pb+Zn / Fe
1% to 5% Pb+Zn / Fe
0.5% to 1% Pb+Zn / Fe
THE Pb%+Zn% / Fe% DISTRIBUTION
1st Bench, S-65 Orebody
FIG. 3.5.VIII.A


67,200
67.000
66.800
66.600
66.400
81.000
81.200
81.400
81.600
81.800
0 100 200ft
0 10 20 50m
more than 5% Pb+Zn / Fe
1% to 5% Pb+Zn / Fe
0.5% to 1% Pb+Zn / Fe
THE Pb%+Zn% / Fe% DISTRIBUTION
2nd Bench, S-65 Orebody
FIG. 3.5.VIII.B


67.200
67.000
66.800
66.600
66.400
more than 5% Pb+Zn / Fe
1% to 5% Pb+Zn / Fe
0.5% to 1% Pb+Zn / Fe
0 100 200ft
0 10 20 50m
THE Pb%+Zn% / Fe% DISTRIBUTION
3rd Bench, S-65 Orebody
FIG. 3.5.VIII.C.

3.6 CONCLUSIONS AND DISCUSSIONS

Conclusion and Discussion of Karsting and Host Rock Features of S-65

The S-65 ore body of the Pine Point ore deposits produced 634,000 tons of combined ore with lead and zinc grades of 1.2% and 5.7% respectively.

The prismatic mineralized breccia occurred in H and I-Facies limestones and dolomites of the Sulfur Point Formation and had its base in the Muskeg Formation.

Breccia fragments are of variable, local origin and include rebrecciated ore and internal sediments. A roof pendant indicates that the cave was closed at the top. Lateral extensions point to the existence of a connection with a network of karst-channels of the South Trend. These lateral extensions show up on the pit walls as breccia filled tunnels in the north (2nd and 3rd benches) and west (3rd bench) or as sparite filled lenses in the north (10° and 30°, 1st bench) and west (1st bench). The composition of internal sediments is evidence for repetitious rebrecciation and ore redistribution within the ore body. A halo of recrystallization and crackle brecciation surrounds the breccia zone.

The south of the ore body was intruded by a sinkhole. During the Pleistocene the ceiling of this part of the cave was open at the top and had tunnels extending

laterally into the ore body. The sink hole material comprises of glacial boulders and detrital lead/zinc ore.

These findings indicate a continuous solution activity from the beginning of karsting until the Pleistocene. Rhodes et al. suggest that the age of the beginning of the karsting was in Mid-Givetian time. It is the opinion of the author that the time of initial karsting is also the time of initial ore deposition. The ore textures give no evidence for the commencement of mineralization in the Givetian and, according to the ore texrures, it could be possible that the mineralizing solutions deposited the ore at a later (e.g. Paleozoic) time. The solutions entered and exited the cylindrical breccia zone via lateral tunnels on different levels. The karst cavity was closed at the top until later, probably Pleistocene time.

Conclusion and Discussion of the Ore Texture Zones of S-65

The mapping of ore textures lead to the identification of five ore zones which are:

The breccia zone,
The zone of intense recrystallization,
The marcasite-rich zones,
The detrital ore zones including
the Pleistocene Sinkhole.

The cross cutting features of these zones reveal a sequence of ore-forming events which were controlled by solutions entering the breccia through lateral karst channels and later through an open ceiling.

Stoping at the location of crossing solution channels along the South Trend resulted in the opening of a cave, which filled with H and I-limestone fragments breaking off the ceiling. The cave was closed at the top and had its base in the J-facies. Initial mineralization was the formation of a breccia matrix consisting of sphalerite and galena growing out of solution. Multiple stages of ore remobilization occurred subsequently which overprinted previously formed ore textures. Remobilizing processes were dissolution, recrystallization, mechanical and chemical redeposition of ore. These processes have obscured textural

zones and the recognition of ore-forming stages is difficult. An approximation of the time relationships between ore-forming stages is presented on Figure 3.6.I.

Sphalerite occurs in a great variety of textures and is wider spread, which indicates that it is more affected by redistributing processes.

Galena textures are of less varieties and confined to smaller areas. Lead is less mobile and after crystallization as galena mainly affected by recrystallization. This observation is of importance, because the plotting of the Pb% distribution provided an outline of the initial ore deposition.

A channel of intense recrystallization cuts through the breccia body from the W-lateral extension to the N-lateral extension. This channel must have remained open long after the initial emplacement of the ore, as it has entirely overprinted pre-existing textures with the exception of the massive marcasite and sinkhole.

Marcasite appears to be very mobile and can be associated with a number of late stages of solution activity. Marcasite occurs in disseminated or massive aggregates.

Disseminated marcasite is common in all zones and occurs by itself or associated with sphalerite. Increased amounts of disseminated marcasite occur in the northwest of the ore body and associated with the W-lateral extension. Disseminated marcasite gradually replaced carbonates and sulphides and has initiated growth preferentially on hydrocarbons and sphalerite. Some of this disseminated marcasite is associated with early rebrecciation and recrystallization. Late stage sphalerite crystals have been found to replace this earlier marcasite.

Massive, sometimes colloform marcasite rapidly filled open spaces where original ore breccia had been removed. This marcasite deposition occurred in late stages, possibly as recent as the formation of the Pleistocene sinkhole. It appears that the sinkhole originated as a cave, open at the top, which filled with glacial boulders derived from the surface, mixed with ore derived from adjacent breccia ore. This ore depletion left caves surrounding the sinkhole. The caves were rapidly filled with massive marcasite. In some portions, this massive marcasite was brecciated and again cemented. There is relatively little marcasite in the sinkhole itself.

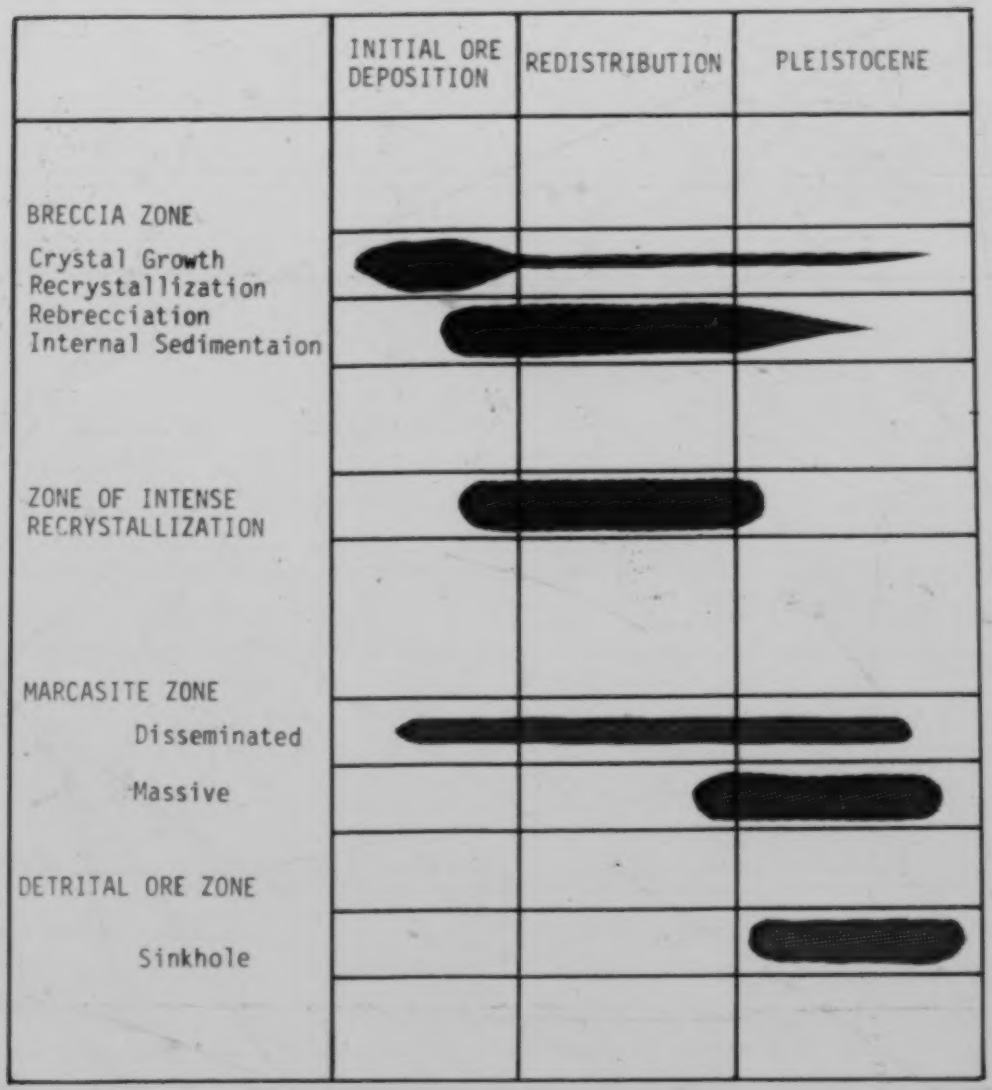


Figure 3.6.I. Genetic / Paragenetic Diagram
The stages of ore formation derived from the study of ore textures.

Conclusion and Discussion of the S-65 Metal and Metal Ratio Distribution Maps

To present the metal and metal ratio distribution in the S-65 deposit, the values from blast-hole analyses were plotted and contoured using the Surface II contouring package.

Pb+Zn%

On all three benches of S-65 the 1.0% Pb+Zn contour line shows oval shaped areas with long axes at 30° azimuth. The long axes of the ovals are approximately 100 m and the perpendicular short axes approximately 70 m long.

On the first bench five ore zones with more than 10% Pb+Zn can be identified: the N, E-central, S, W and SE-ore zones. On the second bench the N and E central ore zones are increased in size, while the W-ore zone has decreased in size. The small SE-ore zone disappears. On the third bench the ore zones with more than 10% Pb+Zn are reduced to one central ore zone.

On the first bench lateral extensions are indicated by a weak bulging of the 1.0% contour line at 20°, 90°, 190° and 290° azimuth. On the second bench, the combined ore distribution map shows lateral extensions protruding further outward compared to those on the first bench. The southern extension seems to widen or to split up into three. On the third bench the low at 230° azimuth is only faintly

visible and the S-ore zone occurs now in the breccia zone between the 230° and 190° lateral extensions. The N and W-ore zones are completely joined and occur in between the possibly related lateral extensions at 20° and 290°. Weakly indicated is also a new lateral extension to the E.

The lateral extensions that were recognized on the Pb%+Zn% distribution maps were plotted as arrows on the three dimensional model of the S-65 ore body (Fig.3.6.II). The arrows do not indicate a direction of flow.

On all three benches of S-65, the sinkhole coincides with the S-lateral extension and the S-ore zone. This theory of mechanically derived ore from immediate surroundings is supported by the Pb/Zn ratio of 1/5 which is characteristic for the S-65 ore body.

Pb%

A 1% Pb contour line contours the outline of the breccia ore of early sulfide deposition. This outline of the early sulfide deposition which is also approximately the outline of the breccia zone was used on the three dimensional model of the S-65 ore body (Fig.3.6.II). The Pb% distribution map of the second bench shows especially well the connection between high grade zone and W and N-lateral extensions.

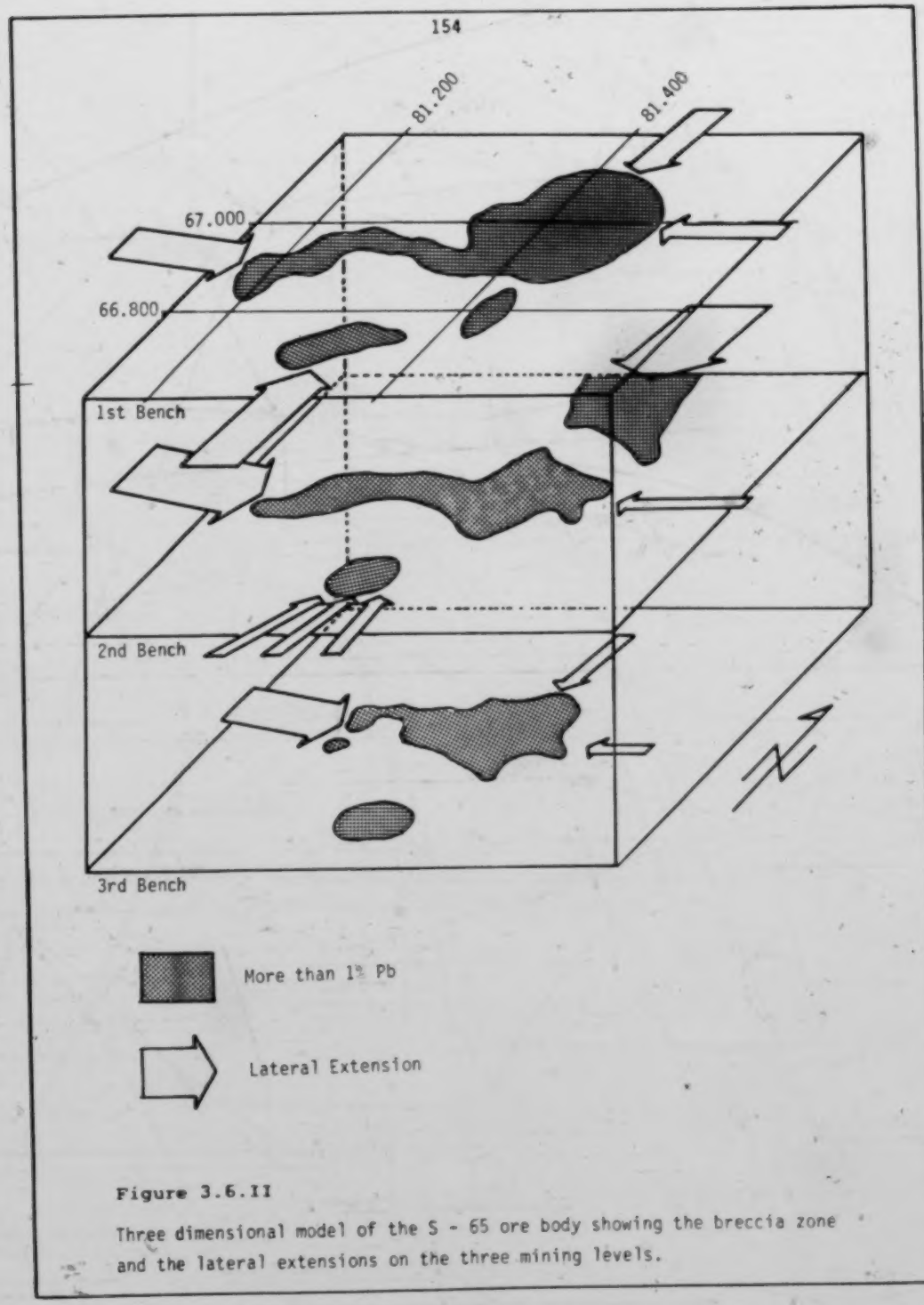


Figure 3.6.II

Three dimensional model of the S - 65 ore body showing the breccia zone and the lateral extensions on the three mining levels.

Zn%

The sphalerite distribution displays a great variety in all ranges of Zn% grades which corresponds with a great variety in sphalerite textures. The cause for this is the greater mobility of sphalerite.

Pb%
Zn%

The Pb/Zn maps do not show the high and low grade ore zones. However, the lateral extensions appear as increases in the relative Zn content. This association of Zn with lateral extensions can be explained by a greater mobility of sphalerite.

Fe%

The Fe distribution is the result of late, overprinting processes. The Fe rim itself is related to the Pleistocene sinkhole which intruded the ore body from the south. The W and S-lateral extensions have, especially on the second bench, noticeably increased Fe% values.

The Correlation of Grade Contours with the Texture Zones of S-65

For the purpose of this correlation the (Pb%+Zn%)/Fe% distribution maps and the textural zonation map were superimposed. The lead + zinc over iron ratio map provides a combination of the previously described maps.

The Pb and Fe maps show that galena ore zones are clearly defined with sharp Fe increases beside the ore highs. There seems to be a inverse relationship between galena and marcasite.

The metal grades of the ore texture zones outlined on Figure 3.4.I were superimposed on the (Pb%+Zn%)/Fe% distribution map. The resulting grades within a zone and the averages for the zones were as follows:

Two Breccia Zones:

0.5 - 1.0	(Pb%+Zn%)/Fe%	538 m^2
1.0 - 5.0	(Pb%+Zn%)/Fe%	2,102 m^2
more than 5.0	(Pb%+Zn%)/Fe%	407 m^2
Total combined area of breccia zones:		3,047 m^2
Total grade average:		3.20 (Pb%+Zn%)/Fe%

Zone of Intense Recrystallization

less than 0.5	(Pb%+Zn%)/Fe%	73 m^2
0.5 - 1.0	(Pb%+Zn%)/Fe%	285 m^2
1.0 - 5.0	(Pb%+Zn%)/Fe%	237 m^2
more than 5.0	(Pb%+Zn%)/Fe%	191 m^2
Total combined area of the zone of intense recrystallization:		786 m^2
Total grade average:		3.02 (Pb%+Zn%)/Fe%

Marcasite Zones

Massive Marcasite

less than 0.5	(Pb%+Zn%)/Fe%	507 m^2
0.5 - 1.0	(Pb%+Zn%)/Fe%	349 m^2
1.0 - 5.0	(Pb%+Zn%)/Fe%	137 m^2
Total combined area of the massive marcasite zones:		993 m^2
Total grade average:		0.80 (Pb%+Zn%)/Fe%

Disseminated Marcasite

1.0 - 5.0	(Pb%+Zn%)/Fe%	76 m^2

It appears that the (Pb%+Zn%)/Fe% grades of the central zones, i.e. the Breccia, Intense Recrystallization and Disseminated Marcasite Zones, is constant between 3.0 to 3.2%. This indicates that the processes of recrystallization and iron enrichment in these zones did not change the average ore grades. However, the high grade ore zone in the Breccia Zone is larger and more pronounced than that of the latter zones which suggests that the processes of recrystallization and iron enrichment evened out the grades by degrading high grade and upgrading low grade ore. While disseminated marcasite is the result of gradual replacement and recrystallization, the massive marcasite appears to have filled open cavities after the removal of pre-existing host and ore. This explains the low averages of the (Pb%+Zn%)/Fe% ratio in the massive marcasite zones.

4. THE K-77 ORE BODY

4.1 Location and History

The K-77 ore body is located 12 miles west of the mill and concentrator, 4 miles west of the next pit, J-69, and 2.5 miles north of the Hay River Road (Fig.2.2.II).

The discovery and production history of K-77 started in 1950, when N. Campbell was drilling fences at 5,000 feet intervals. He came as close as 400 feet to the high grade zone of the K-77 ore body. In 1960 an I.P. survey with a 250 feet line spacing produced an anomaly over the ore body. Follow up diamond drilling in 1966 resulted in an indication of low grade mineralization. Further follow-up drilling in 1979, initiated by a property wide core logging review, penetrated ore grade material in two holes (holes #5 and #6). Ore outline drilling resulted in total proven ore reserves of 647,700 tons with 3.9% Pb+Zn.

Mining of the first bench of K-77 began in September 1981; the geology, ore textures and metal distribution were mapped by the author at this time. The earlier I.P. survey and diamond drill core logging were utilized for the interpretation of the ore body and are shown on maps below.

4.2. The General Geology of the K-77 Ore Body

Subcrop Geology

On the subcrop map (Fig.2.2.II) it can be seen that the K-77 pit lies on a prominent high which exposes H and I-limestones which are unconformably overlain by the Watt Mountain Formation to the north and south. This high is a property wide feature and other pits such as J-69, K-62 and K-53 lie along it. The work of J.A. Lantos (1983) has shown that this high of the H and I-limestones corresponds with a depositional high referred to as the PB Trend. The Pb Trend is the most northern karst development within the Main Trend.

Stratigraphy

K-77 is a prismatic ore body in the Main Trend and occurs in the Sulphur Point Formation. The mineralization occurs in a paleo-collapse zone within the H and I-facies.

4.3. Diamond Drill Core Evaluation

Core drilled in 1979 was first logged by staff geologists of Pine Point Mines Ltd. These cores were subsequently relogged by the author. A pit scale subcrop map and a cross section were produced.

The subcrop map shows that the ore body occurs in an east-west trending solution zone within H and I-limestones. The solution zone widens around the mineralized zone to over 100 m in a north-south direction. Internal

sediments were recognized in the solution zone to the east and west of the high grade zone. Cavity filling materials, deposited by collapse and dissolution, were recrystallized and impregnated or replaced by sulfides. To the south and east of the high grade ore zone, abundant marcasite was found. An envelope of Presqu'ile dolomite forms the boundary between the solution zone and unaltered host rock.

The pit scale cross section (Fig.4.3.I) cuts in a north-south direction, perpendicular to the trend of the solution zone, through the high grade ore zone of the deposit. It was recognized that high grade ore does not only occur in the central main collapse zone, but also in the lateral extensions or "wings" of the collapse zone. The coarse Presqu'ile sparite transition zone is underlying and enveloping the solution zone. Cavities in the underlying Presqu'ile sparite have been filled with internal sediments. The diamond drilling also discovered a thickening of the directly underlying D3-horizon. The D3-facies has a breccia lithology and is commonly found at the top of the Pine Point Formation. This thickening of this underlying horizon could have been the cause for a karst formation and collapse zone on top.

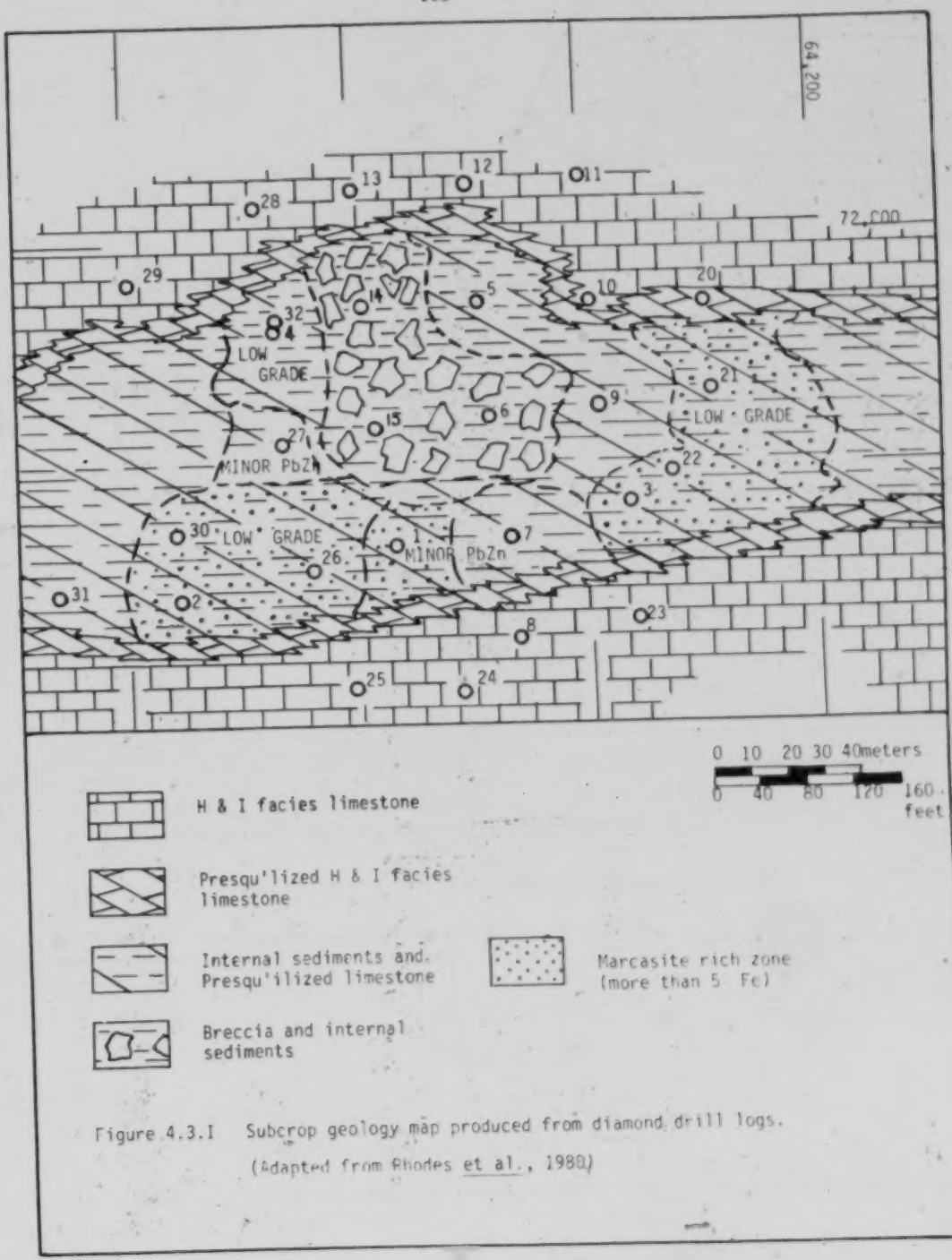


Figure 4.3.I Subcrop geology map produced from diamond drill logs.

(Adapted from Rhodes et al., 1980)

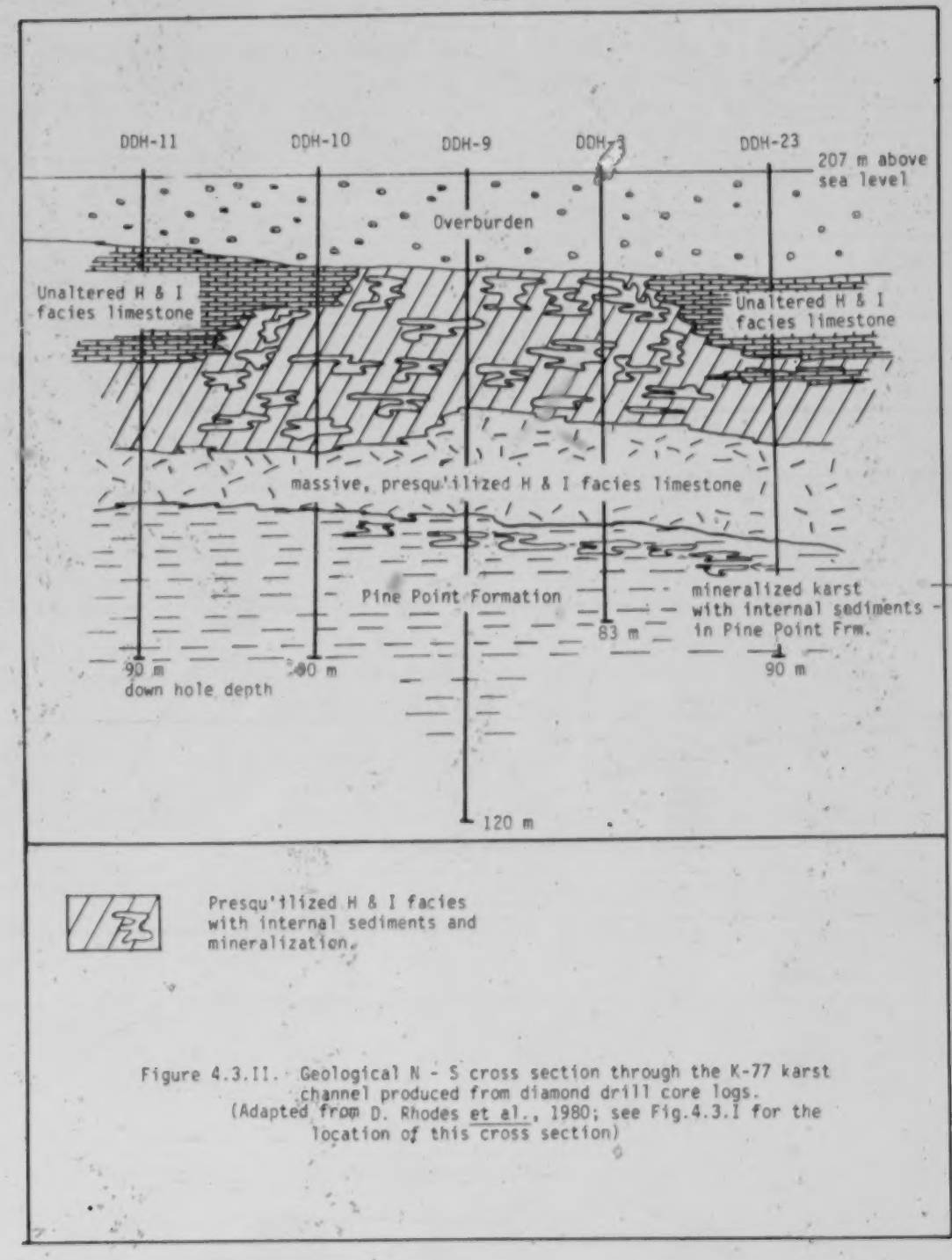


Figure 4.3.II. Geological N - S cross section through the K-77 karst channel produced from diamond drill core logs. (Adapted from D. Rhodes et al., 1980; see Fig.4.3.I for the location of this cross section)

4.4. Karsting and Host Rock Mapping on Pit Scale

During the excavation of the first bench of K-77 the digging faces were mapped daily: the resulting geology of the bench is shown on Figures 4.4.I and II. The mapping of the host rock on the first bench resulted in the recognition of six zones with characteristic karst geology. These zones are:

- The zone of unaltered H and I-limestone
- The peripheral zone
- The internal sediment zone
- The main collapse zone
- The zone of intense recrystallization
- Zones of modern karsting

First the host rock lithologies of the various zones will be described. The ore textures in each of these zones will be dealt with separately.

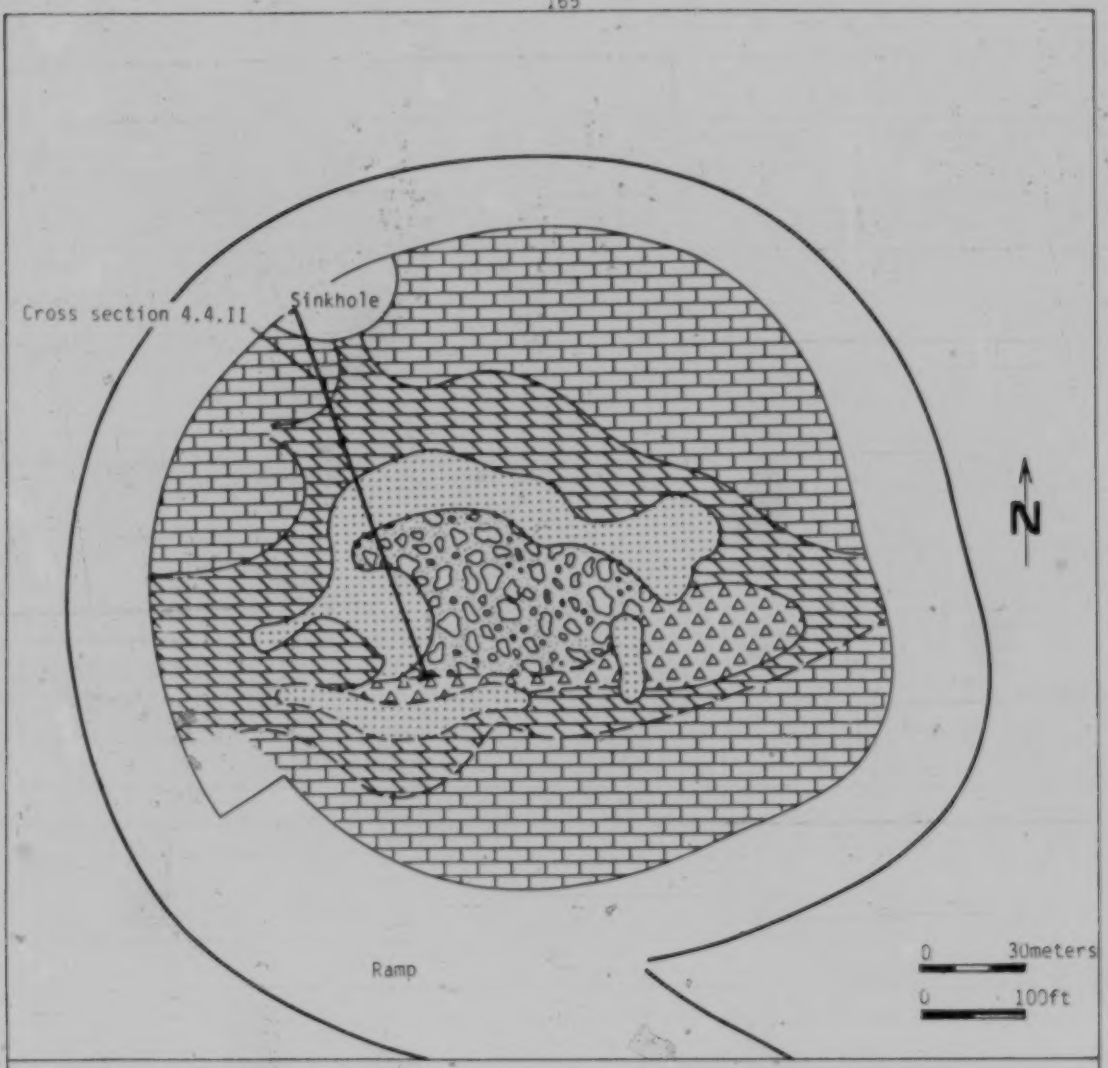


Figure 4.4.I. Host Rock Geology and Ore Zones of the K-77 First Bench

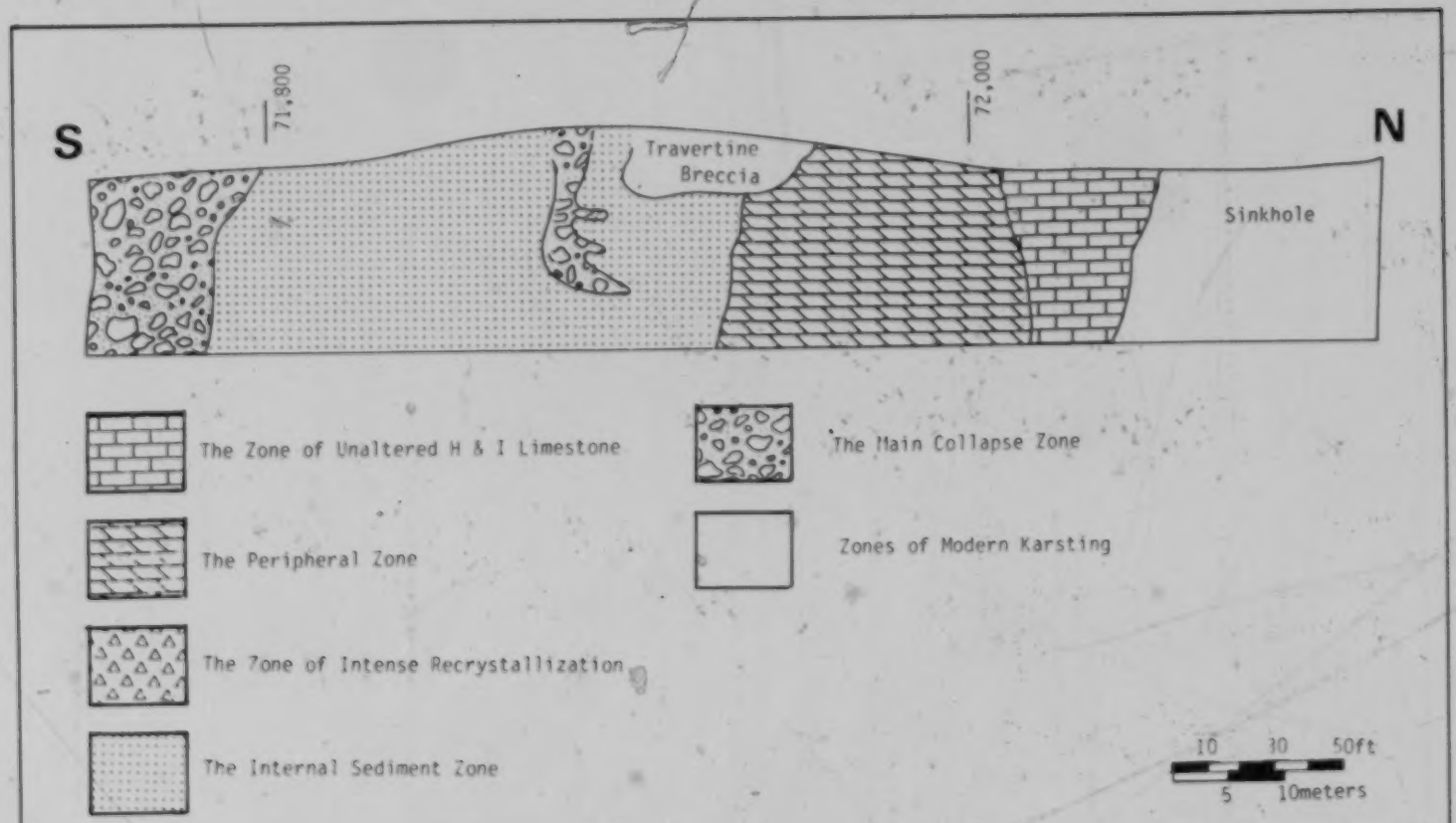


Figure 4.4.II. Cross section through the north-west portion of the K-77 ore body. 170° azimuth, see Fig.4.4.I for location.

The Host Rock Lithologies

(a) The zone of the unaltered H and I-limestone. The cross section begins in the north in unmineralized H and I-limestones. These limestones are fossiliferous and buff grey-brown in colour (Fig.4.4.III). Fossiliferous portions of the limestone are hydrocarbon rich and these darker, also more argillaceous areas, delineate bedding planes in the usually quite massive mudstone. Green shales of the Watt Mountain Formation have been washed into the limestone through fractures and channels, and form 10 to 30 cm thick horizontal layers. These layers are a local feature and are discontinuous on a larger scale.

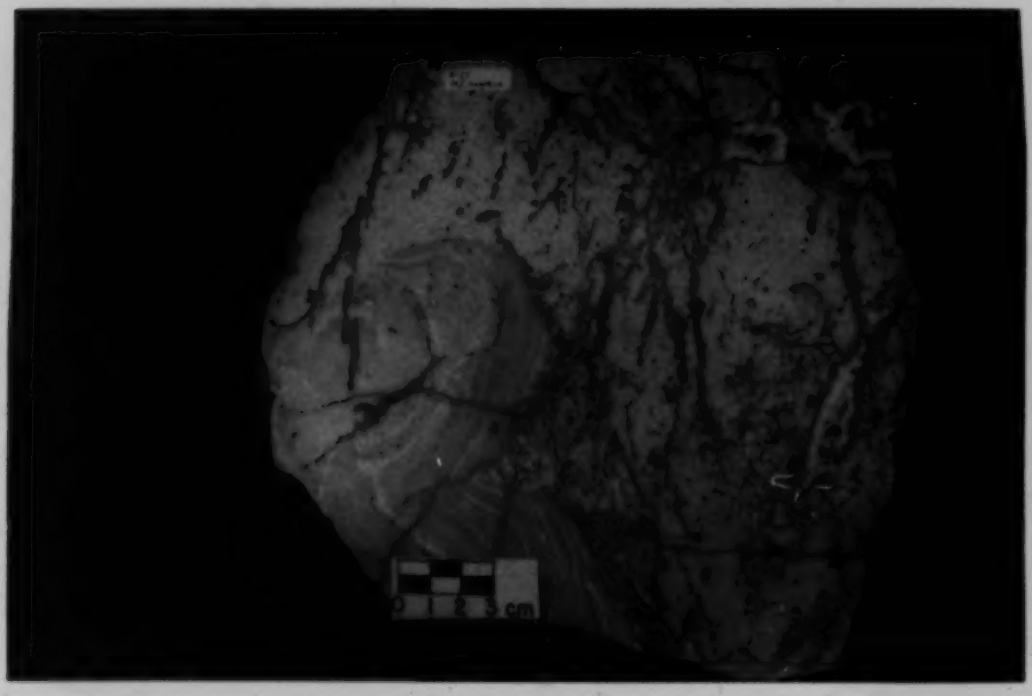


Figure 4.4.III. H and I-limestone

(b) The peripheral zone. The transition from unaltered H and I-limestone to the dolomitized zone is very rapid and not related to bedding planes. The limestone is fractured and then recrystallized to coarse Presqu'ile dolomite. This Presqu'ilization usually introduces boxwork textures (Fig.4.4.IV). This texture, as previously described, is a coarse grained, white or grey dolspar delineating the location of former fractures. The various possible steps from unaltered host to boxwork dolomite have been described by Dunsmore (1973).

(c) The internal sediment zone. The next zone south on the cross section is marked by numerous patches of internal sediments. The sediments are grey-white, medium grained and well sorted. They are cemented by carbonate and partly recrystallized to white or blue-grey dolspar. The areas between the internal sediment patches consist of coarse white and blue-grey dolspar, irregular masses of marcasite and large pore spaces. Brecciation is rare in this zone.

Figure 4.4.IV. Boxwork type recrystallization in the peripheral zone.

(d) The main collapse zone. The transition from the previous zone into the main collapse zone is again quite rapid. Brecciation, recrystallization and internal sedimentation have occurred repeatedly in various orders destroying or overprinting any previous host rock or ore textures. Breccia fragments mainly originate from the Watt Mountain Formation; the internal sediments of this zone vary in colour, grain size and sorting. This variety points towards a more complex history of internal sedimentation in comparison with the single type internal sediments of the previous zone.

(e) The zone of intense recrystallization. South of the main collapse zone and within the east west trending solution zone, intense recrystallization overprints parts of the internal sediments and of the collapse zone. White and blue-grey sparite occurs in great abundance and characterizes a zone by itself.

(f) Zones of modern karst activity. In the north of the K-77 ore body, a sinkhole occurs. It measures approximately 20 m in diameter and is filled with fine grained, well sorted and uncemented sand. The sand consists of quartz and carbonate grains and is yellowish brown in colour. The age of this sinkhole fill is uncertain, but this sinkhole is chronologically the latest cross cutting feature before the forming of the present muskeg cover.

Older than, and overprinted by the sinkhole, are

sinter filled tunnels (Fig.4.4.V). The calcareous sinter growth has filled open cavities with bulbous masses of carbonate crystals.

Figure 4.4.V. Cavity filled by sintering during modern karst activities

Summary of the General and Pit Scale Geology of K-77

K-77 is a prismatic ore body along the Main Trend, and occurs in the H and I-facies of the Sulphur Point Formation. Diamond drilling at the K-77 location revealed an east-west trending solution zone with a paleo collapse zone as wide as 100 m. Drilling and pit mapping revealed the following mappable geological zones:

-Unaltered H and I-limestone

-A halo of Presqu'ile dolomite occurs around the ore body (peripheral zone).

-A central high grade core (main collapse zone).

-Internal sediments to the north, west and south of the main collapse.

-Marcasite enrichment to the south and east of the main collapse.

-Intense recrystallization along the south and east of the collapse zone.

-Modern karst activities are reflected by sinter zones and a sinkhole.

The host rock geology and ore zones of K-77 are shown on Figure 4.4.I and Section 4.4.II.

4.5. Ore Textures of the K-77 Ore Body

Introduction

In the process of pit mapping, six geological units were recognized. Mineralization occurs only in four of these; the sinkhole and the sinter channel are not mineralized. The mineralized zones are (Fig.4.4.I).

The peripheral zone
The internal sediment zone
The recrystallization zone
The collapse zone

During the mining of the first bench of K-77, it was found that each of the above four geological zones also has characteristic marcasite, galena and sphalerite textures. These textures are described and explained in the following paragraphs.

After the identification of the various ore textures, the diamond drill core of K-77 was relogged and a cross section was produced showing the distribution and zonation of these ore textural zones beyond the first bench (Fig.4.5.XXXI).

The Sulfide Textures in the Peripheral Zone

As shown on the geology map (Fig.4.4.I), the peripheral zone occurs as a halo around the K-77 collapse zone and also outlines the east-west trend of the solution zone. There is an extension of the peripheral zone to the north which terminates in a sinkhole of modern age.

With the first appearance of porosity in boxwork dolomite, marcasite is introduced. The fine crystalline aggregates of the iron sulfide occur along the borders of blue grey dolomite-sparite as layers or patchy accumulations (Fig.4.5.I). Marcasite also grows in spaces left open between coarse crystals of white or blue-grey dolomite sparite. Figure 4.5.II shows this marcasite in a polished mount: It can be seen that the crystals grow in small rounded aggregates. The individual crystals are euhedral and grow into open cavity space. Under crossed polarisers annealing twins can be observed, representing the uniting of two or more simultaneously growing, neighboring crystals. Hydrocarbon stains and minute bands of argillaceous material are common in the cavities of the peripheral zone. Recrystallization of the H and I-limestone in this zone causes the accumulation of these substances (Fig.4.5.III). The photograph shows a front of advancing recrystallization in a carbonate rock. The newly formed crystals are characteristically clear and larger in size than the original carbonate crystals.

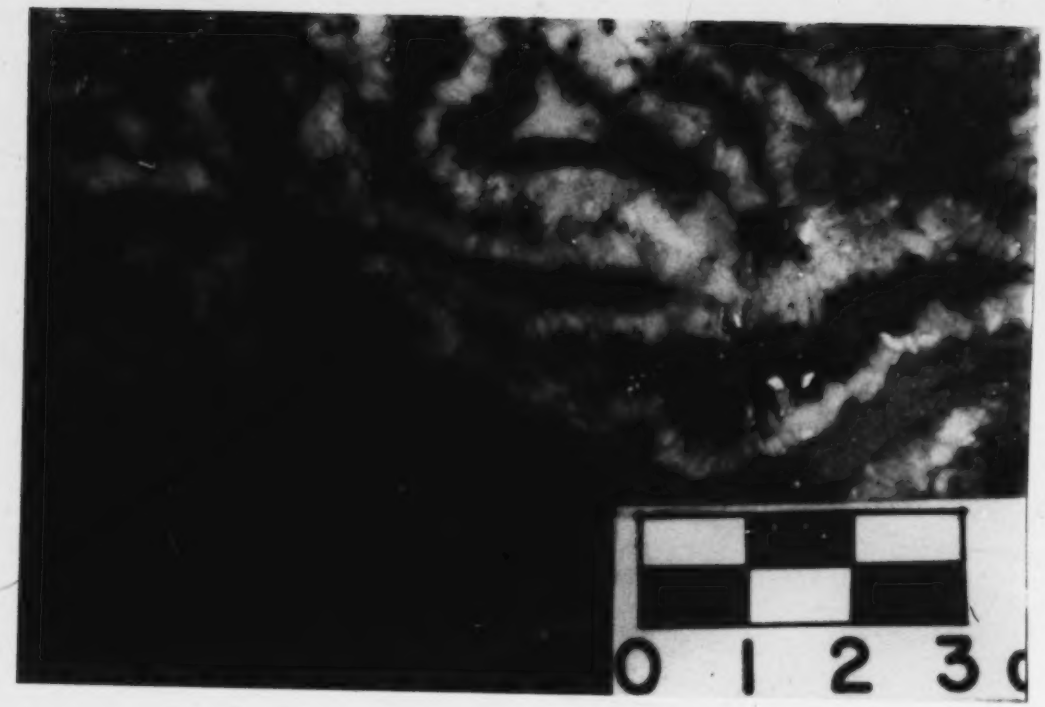


Figure 4.5.I (Sample PP marc) Handspecimen from the peripheral ore zone. Marcasite is following the hydrocarbon-stained fractures and blue-grey sparite which occur at fronts of recrystallization. Scale bar in cm.

Figure 4.5.II (Sample #c1/1) Polished mount. Patches of euhedral marcasite crystals growing into open space. Scale: 1cm = 1mm

The coarse recrystallization of carbonates in the Pine Point Reef Complex is referred to as Presqu'ilization. The coarse grained dolomite is called dolomite sparite or

just sparite when uncertain whether dolomite or calcite is present. Particles of argillaceous material and hydrocarbons which were trapped within the original rock, are pushed away by the recrystallization and are concentrated along the recrystallization front. At the junction of two advancing fronts, linear cavities are a common feature. In these cavities the "rejected" argillaceous and hydrocarbon substances accumulate. If the cavities are interconnected, solutions can travel through the system and remove the accumulated substances. Iron rich solutions travelling through the system precipitate marcasite preferentially in the hydrocarbon rich cavities (Fig.4.5.III). Assuming continuous recrystallization since the initial karst development, the hydrocarbon has been continuously released from the recrystallizing rocks. This process can provide H_2S which is required to precipitate the sulfides out of the solutions. Rhodes et al., 1984, suggest that the karsting began during the Mid-Givetian time.

Liquid hydrocarbons can be trapped in shard like cavities between sparite crystals. Consecutive marcasite precipitation can result in fine grained aggregates of marcasite pseudomorph after the hydrocarbon inclusion.

Galena or sphalerite mineralization is very rare in this peripheral zone.

Figure 4.5.III (Sample c3/x). Thin-section. Advancing recrystallization cleans the crystals and concentrates the impurities at the front. In this way hydrocarbons were concentrated which are followed by marcasite.
Scale: 1cm = 2mm

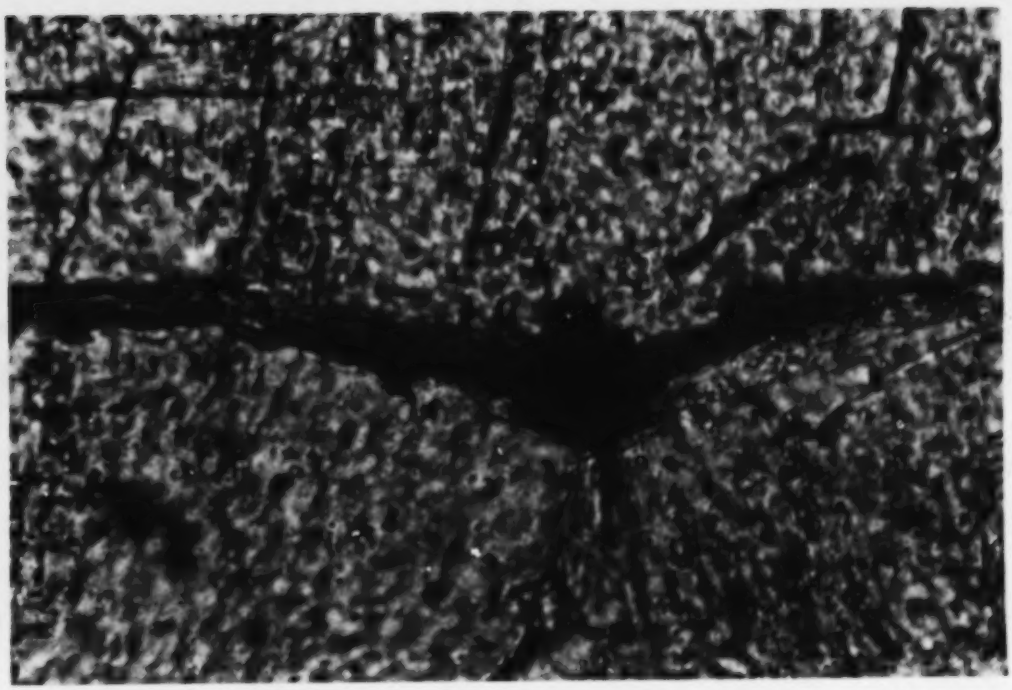


Figure 4.5.IV (Sample c3/x). Thin-section showing a crystal of marcasite growing at the hydrocarbon-stained contact between two recrystallized dolomite crystals. Scale: 1cm = 0.5mm

The Ore Textures of the Internal Sediment Zone

This ore zone as outlined on Figure 4.4.I occurs in the north, east and west adjoining the central collapse zone. In the south the internal sediment zone has been overprinted by the recrystallization zone and only relics of the internal sedimentary textures can be found.

Galena ore textures in the internal sediment zone are the result of:

a.) Synsedimentary, detrital deposition,

b.) Continuing growth of existing (or on top of existing) galena crystals without new nucleation.

The most characteristic texture in this zone is large, euhedral galena cubes (Fig.4.5.V). These crystals grow on top of more or less intensely recrystallized internal sediments and are covered by coarse white or grey dolomite sparite. The euhedral and undeformed character of these crystal surfaces suggests growth into open space. The galena crystals grew outwardly after deposition of the crystal seeds on the top surface of the internal sediment. The authigenic growth can be recognized by the lateral impingement boundaries between the simultaneously growing, large crystals.

Fig.4.5.V (Sample PPGal). Hand specimen from the Internal Sediment Zone. Large euhedral galena crystals are located on the top of the sediment. Scale bar in cm.

The galena crystals rest on mostly recrystallized internal sediment. The bases of the galena crystals (Fig.4.5.VI) are also euhedral which indicates that the growing crystals were free floating on the internal sediment. Recrystallization occurred after the galena crystals were in place.

Figure 4.5.VI (Sample c1/7). Polished section showing the base contact of euhedral galena on recrystallized internal sediment. Scale: 1cm = 0.5mm

The presence of smaller, detrital galena crystals within the internal sediment also suggests that the large crystals on top were seeded from minute, detrital galena. After this seeding, the energy level and the lead concentration of the solution remained constantly high, in a quiet environment, over a long period of time to allow the large crystals to grow. The energy level did not rise high enough to cause any nucleation of new galena crystals besides the seeds already supplied by detrital sedimentation.

The solution which caused the large galena crystals to grow on the surface also percolated through the internal sediment and again was not concentrated enough to nucleate new galena crystals but had to build onto existing, suitable seeds. Suitable, detrital galena seeds can be observed within the sediments. Even though transported, the detrital crystals are euhedral, as galena is brittle and tends to fracture along its cleavage. Within the sediments only intergranular space is available and after the start on the detrital galena, the secondary or authigenic galena will grow interstitially into the dolomite sparite (Fig.4.5.VII). Carbonate crystals were poikilotopically enclosed within the galena crystals.

After the internal sedimentation and authigenic galena growth, any remaining cavities at the top of the sediment were infilled with sparite. Occasionally this

sparite will separate and lift coarse galena crystal off the internal sediment. These galena crystals will then occur free floating within the sparite.

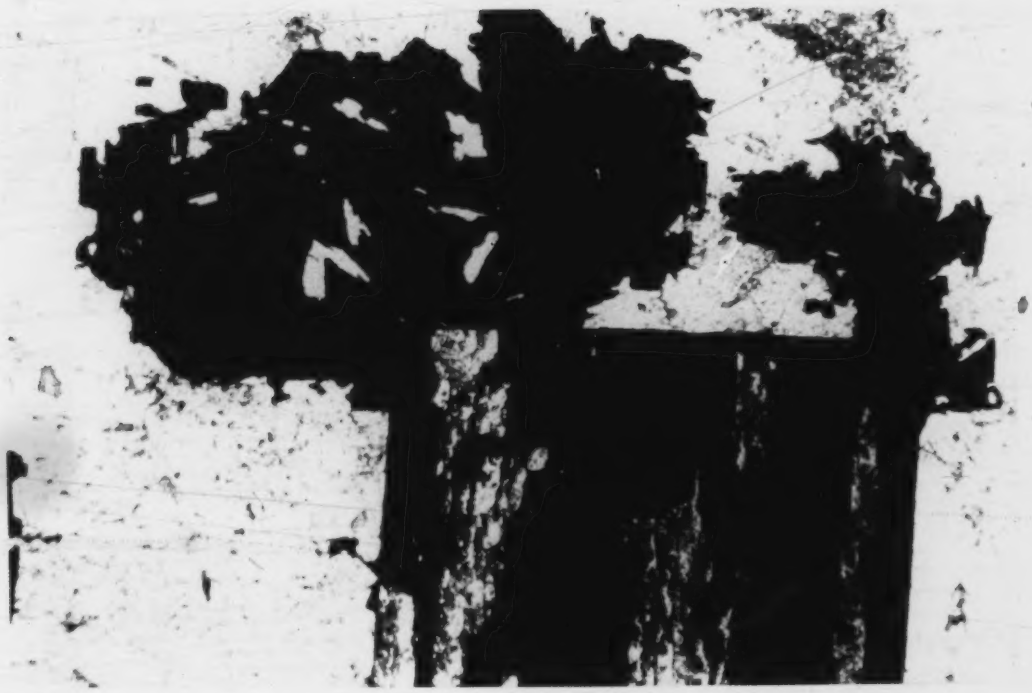


Figure 4.5.VII (Sample c3/x). Thin-section of a detrital, euhedral galena crystal with secondary, anhedral galena. overgrowth.
Scale: 1cm = 0.5mm

Sphalerite ore textures in the internal sediment zone are the result of:

a) Synsedimentary, detrital deposition,
b) Postsedimentary, authigenic nucleation and growth,
c) Recrystallization of syn- or post-sedimentary textures.

Whole synsedimentary sphalerite crystals which were reworked, mechanically deposited and originate from previously formed ore. While galena crystals are brittle and fracture parallel to cleavage during transport, sphalerite will abrade and develop sphericity and roundness. The crystal surfaces were fractured and pitted as the result of the mechanical transport. It was frequently found that the grain size of the sphalerite was comparable to that of the carbonate grains of the internal sediment. This suggests a related history of transport and provenance of the synsedimentary minerals.

Subsequent to the emplacement of the internal sediments, percolating solutions caused further sphalerite growth within the sediment. As was the case with galena, the solutions in this case were not strong enough to nucleate new seeds, but suitable existing crystals were used for

continued growth. The secondary growth of sphalerite occurred on existing sphalerite crystals as overgrowth (Fig.4.5.IIX). The overgrowth can be differentiated by the more intense reddish brown colouring, while the primary sphalerite is pale in colour, which was possibly caused by pre-overgrowth leaching.

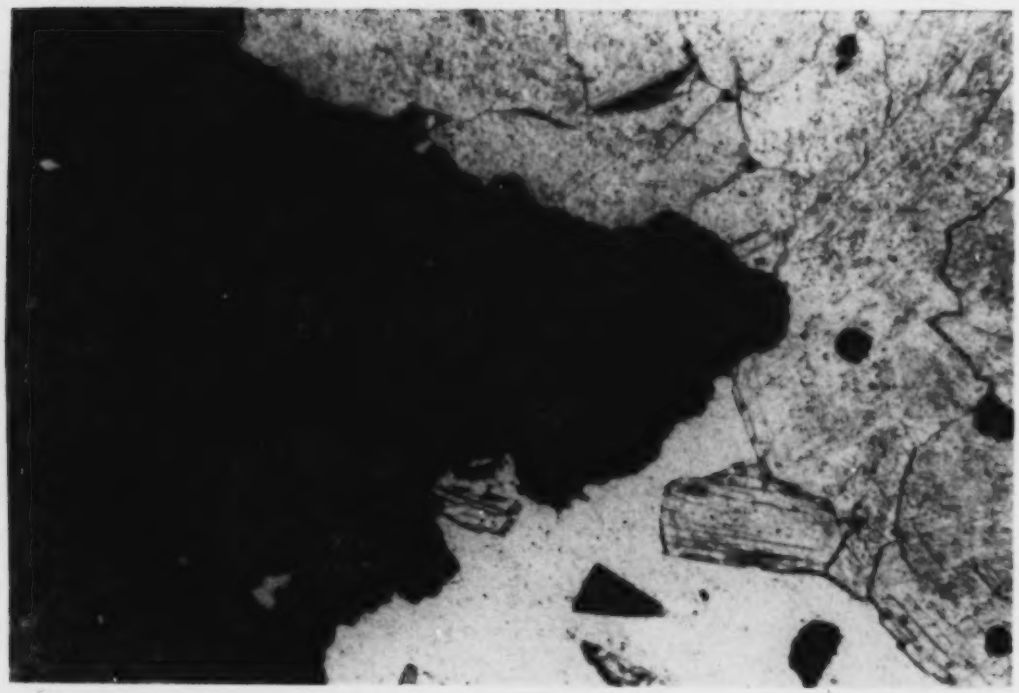


Figure 4.5.IIX (Sample c3/x). Thin-section of a sphalerite crystal with sphalerite overgrowth. Scale: 1cm = 1mm

A characteristic sphalerite ore texture is formed by 1 to 3 cm large patches of disseminated sphalerite grains (Fig.4.5.IX). The microscopic study (Fig.4.5.X) shows, that the patches comprise of primary, synsedimentary sphalerite grains, which were joined by overgrowth. This joining creates a spherical, patchy disseminated aggregate.

Fig. 4.5.IX Patchy disseminated sphalerite grains occur within the sediment. Scale bar in cm.

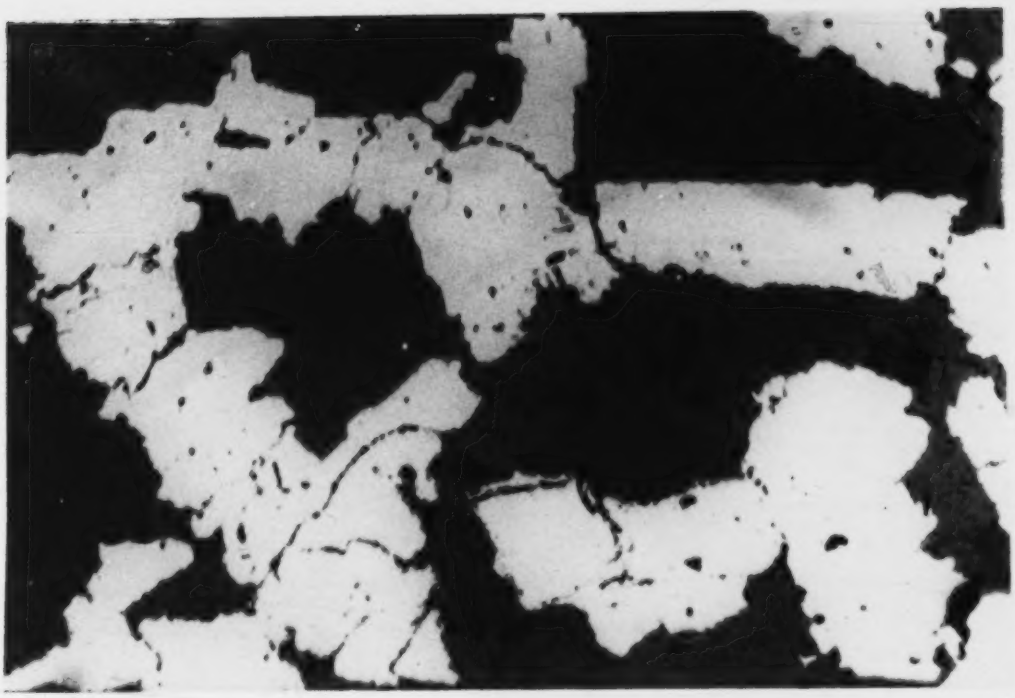


Figure 4.5.X. Polished section of patchy, disseminated sphalerite. Scale: 1cm = 1mm

The tendency towards spherical shapes in aggregates or even in single crystals is because the surface to volume ratio is then at a minimum. Ideally, a sphere would be constructed by isotropic accumulation. The surface energy across the periphery of the crystal or the aggregate must be uniform to allow the uniform accumulation of atoms or molecules. Rounded crystals or crystal aggregates as a result of free growth in open space are rare, but spherical aggregates as a result of recrystallization, to reduce the energy level of the primary system, are common and the

patchy disseminated sphalerite within the internal sediment is one example. The microphotograph of the sphalerite patches shows that crystal overgrowth joins the sphalerite crystals to irregular dendritic aggregates. Initially this random, dendritic joining of crystals introduces a minor reduction of the total energy of the crystal aggregate. But the high surface to volume ratio of this dendrite is extremely unstable. In tending towards a greater stability, the aggregate will during further annealing or recrystallization attempt to increase the crystal size of the dendrite components, and to fill in the remaining interstices between the branches with sphalerite.

Figure 4.5.XI shows the energy reduction of a dendrite by the introduction of twin boundaries. During recrystallization of the dendritic sphalerite, it was more convenient to shift the neighboring crystals into a twin orientation than to rearrange the molecules to form a single crystal.

Some of this authigenic sphalerite growth and recrystallization might have required open spaces, and probable occurred during the recrystallization of the internal sediment, when cavities were still present.

Besides using pre-existing sphalerite for continued crystal growth, sphalerite can also use marcasite as a crystal seed. After this initiation of growth, the sphalerite will attach itself to (Fig.4.5.XII), or replace

the marcasite crystal. In the case of replacement sphalerite can advance within twin boundaries of the marcasite (Fig.4.5.XIII). Such replacement develops sphalerite pseudomorphs after marcasite.

Marcasite in the zone of internal sedimentation was found in authigenic growth, especially concentrated in hydrocarbon-stained cavities. The iron sulfide also occurred in intercrystalline spaces of recrystallized internal sediments. In this case, minute grains of marcasite crystallized in patches and irregular networks, outlining the crystals of the sparite.

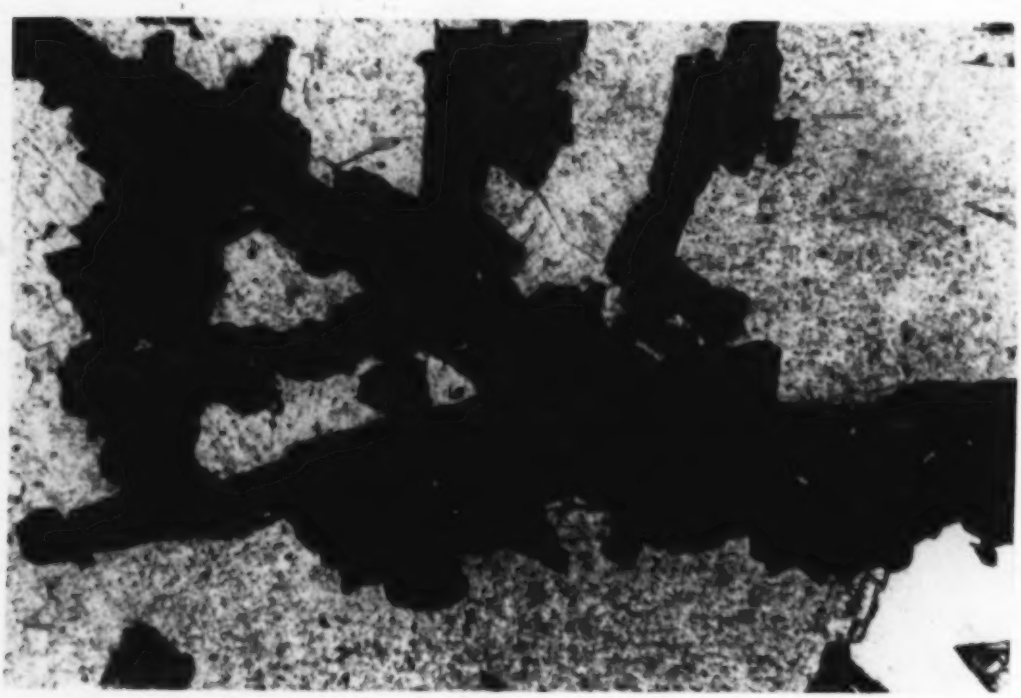


Figure 4.5.XI (Sample c3/x). Thin-section. Patchy, disseminated sphalerite connected by dendrites in internal sediments. Twinning reduces energy.
Scale: 1cm = 1mm

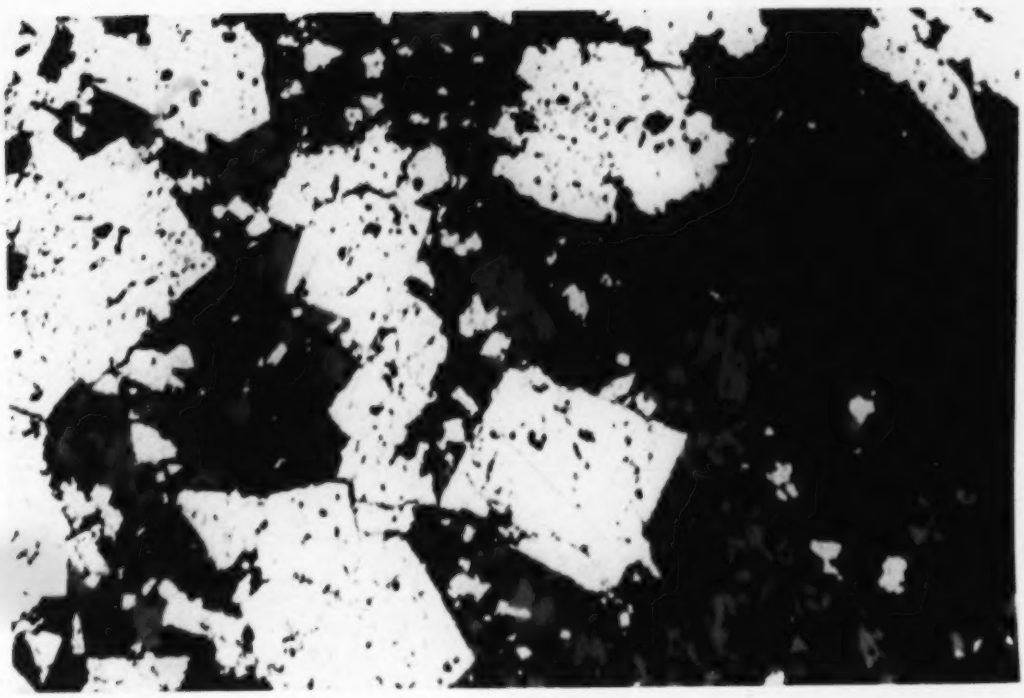


Figure 4.5.XII (Sample c1/11). Sphalerite attached to marcasite crystals within internal sediments.
Scale: 1 cm = 1mm

Figure 4.5.XIII (Sample c1/11). Sphalerite replacing marcasite in internal sediments. Replacement along twinning and pseudomorphism. Scale: 1 cm = 0.5mm

The Ore Textures Formed by Recrystallization

The zone of intense recrystallization occurs on the second bench of K-77 directly south of the main collapse zone. The zone is elongated in shape with a total length of 120 m and a width of up to 35 m. The zone is parallel to and within the east-west trending solution zone. On the map (Fig.4.4.I) it can be seen that the zones of recrystallization thickens substantially in the eastern portion of the ore body.

In this zone, blue-grey and white sparite comprise the predominant and characteristic host material. Mineralization occurs peripherally around ghost remnants of partially dissolved or recrystallized, pre-existing material, and as isolated crystals or aggregates within the coarse sparite. The mineralization takes the form of an outwardly growing, mono-mineralic, poly-crystalline aggregate of sphalerite crystals. Sphalerite typically forms a rimming type texture. Simultaneous crystal nucleation and growth produced irregular layers of relatively equant crystals ranging in size from 2 to 10 mm. These layers of equant crystals result in a linear, mosaic texture. Mechanical derivation of these mosaic layers can be excluded, because detrital type textures like a capping texture are lacking. Instead, the remnant material of the breccia fragments is enclosed by an envelope of constant thickness at all sides. It is possible that sphalerite

recrystallization is also partially responsible for the uniform grain size and the mosaic texture of the sphalerite.

In many cases, after the formation of the mosaic sphalerite envelope, white sparite, galena and sphalerite crystallized simultaneously. Impingement textures between the outwardly growing crystals formed as the result of this competitive, poly-mineralic crystallization. The outwardly growing sparite crystals impinged with the sphalerite and galena, and terminated their crystal growth such that the sulfides hardly ever reached a size larger the 5mm. The lack of exposed crystal surfaces caused an increase in solution concentration and as a result of that increase, nucleation. The nucleated seeds settled as close as possible above the terminated sulfide crystals, because even the slightest touch or even closeness of two crystals reduces the energy level of the system. The newly formed seeds again grow to an approximate size of 5 mm when they are terminated as before. Repetition of this process leads to the peripheral growth of a dendritic aggregate on a relict breccia fragment (Figs.4.5.XIV and XV). Both sphalerite and galena can form such dendrites.

Figure 4.5.XIV (Sample x/1). Handspecimen. Irregular galena dendritic aggregate. Scale bar in cm.

Figure 4.5.XV (Sample x/2). Thinsection. Irregular galena dendritic aggregate growing in competition with sparite. Scale: 1cm = 1mm

Figure 4.5.XVI (K-77-D). Handspecimen. Capping of breccia fragments in the zone of recrystallization.

Another ore texture is formed by the capping of relict breccia fragments. Capping by detrital sulfide deposition was already observed in the S-65 ore body, where it was found in the main collapse zone (Fig.4.5.XVI). Sphalerite crystals were deposited detritally and have formed caps on the upper surfaces of relict breccia fragments shows sphalerite crystals that accumulated on the upper surface of a breccia fragment. The fragment itself was at a later stage replaced by sparite. It is important to note that this sphalerite capping occurred in open,

interfragmental space by solution traction currents. This solution zone is within the east-west trending solution zone which is outlined by the peripheral zone. The individual crystals that comprise the maps can be up to 4 cm in size and these crystals are very similar to the sphalerite stars, which were observed in the ore zone of recrystallization of S-65. The sphalerite stars are also found in K-77 and it is possible that the growth of the cavity filling sparite separated and lifted the individual crystals from capping sphalerite layers and pushed them into the cavities where the isolated stars were enclosed by sparite. The size of the sphalerite stars increased through recrystallization (Fig.4.5.XVII).

After growth and recrystallization of the sphalerite stars and caps, the surrounding sparite exerted pressure on the sphalerite crystals. As a result, the sphalerite shows deformation twin. Characteristically, this type of twin exhibits irregular discontinuous lamellae, which seems to be independent of any crystallographic structure. Deformation twinning is a way of reducing the energy in the interior of a crystal, where the energy level was raised by outside pressure (Fig.4.5.XIIX). In sphalerite crystals deformation twin lamellae often appear purple in colour.

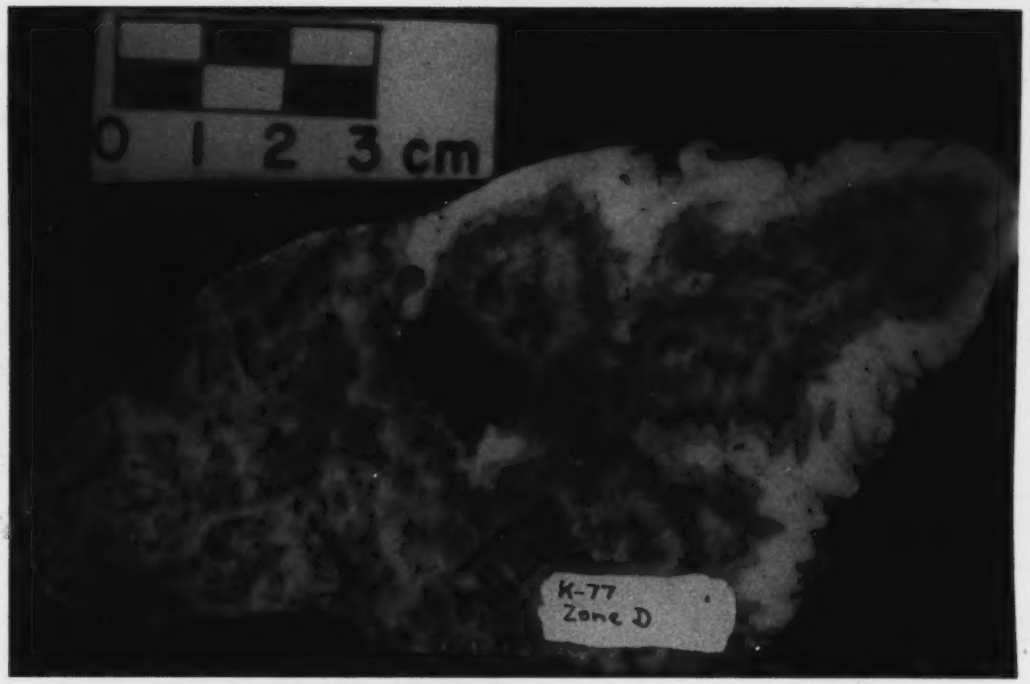


Figure 4.5.XVII (Sample PPstar). Handspecimen. Sphalerite star in sparite.

Figure 4.5.XIIX Thin section. Deformation twin in sphalerite star. Scale: 1cm = 1mm

Galena crystals floating in the blue-grey or white sparite are usually broken up as a result of pressure from the surrounding sparite. Occasionally galena crystals of 0.5 to 2 cm size are found isolated within the sparite. They show rounded dissolution pits and might be remnants of euhedral galena cubes which originated in internal sediments. The internal sediments cannot be recognized and probably were completely replaced by sparite.

The Ore Textures of the Main Ore Zone

The main ore zone occurs in the main collapse zone, in which most solution activity has taken place. The Main Ore Zone is approximately circular in shape with a diameter of 50m (Fig.4.4.I).

The overwhelming amount of repeated cross-cutting textural relationships make it impossible to assign certain textures to certain stages of mineralization. Stages can only be followed on a local scale of meters, beyond which they are again overprinted. The sulfides occur in the following settings:

A. Rimming and cementing breccia fragments
B. Filling large primary or secondary open spaces
C. Associated with recrystallization
D. Associated with internal sedimentation

A. The Rimming and Cementing of Breccia Fragments

A major mineralizing process occurred directly after brecciation and it enclosed breccia fragments directly with sphalerite and galena. Extreme supersaturation caused rapid precipitation of sphalerite seeds, which were covered by following generations of seeds, before crystal growth could take place. In this way colloform sphalerite was deposited. The crystal seeds, being almost weightless, did

not settle by gravity, but were attracted by existing seed aggregates. This attraction explains the enclosure of breccia fragments from all sides rather than the forming of layers due to gravity settling. Alternating colour-bands of colloform sphalerite either indicate a change in sphalerite composition, slower or faster rate of seeding or incipient crystal growth. Crystal growth usually introduces dark brown translucent layers, different from the very fine grained milky beige (Fig.4.5.XIX). Polished mounts of colloform sphalerite show that the boundary lines between neighboring, colloform sphalerite masses are irregular and interlocking (Fig.4.5.XX). These types of boundaries are not typical for primary crystal or aggregate boundaries, and it is likely, that the colloform sphalerite was recrystallized and that the irregular boundaries are the line of collision of two recrystallization fronts.

Figure 4.5.XIX (K-77-2C). Handspecimen from the main collapse zone. The inter-fragmental space of the breccia has been filled by colloform sphalerite and crystalline sphalerite and galena.

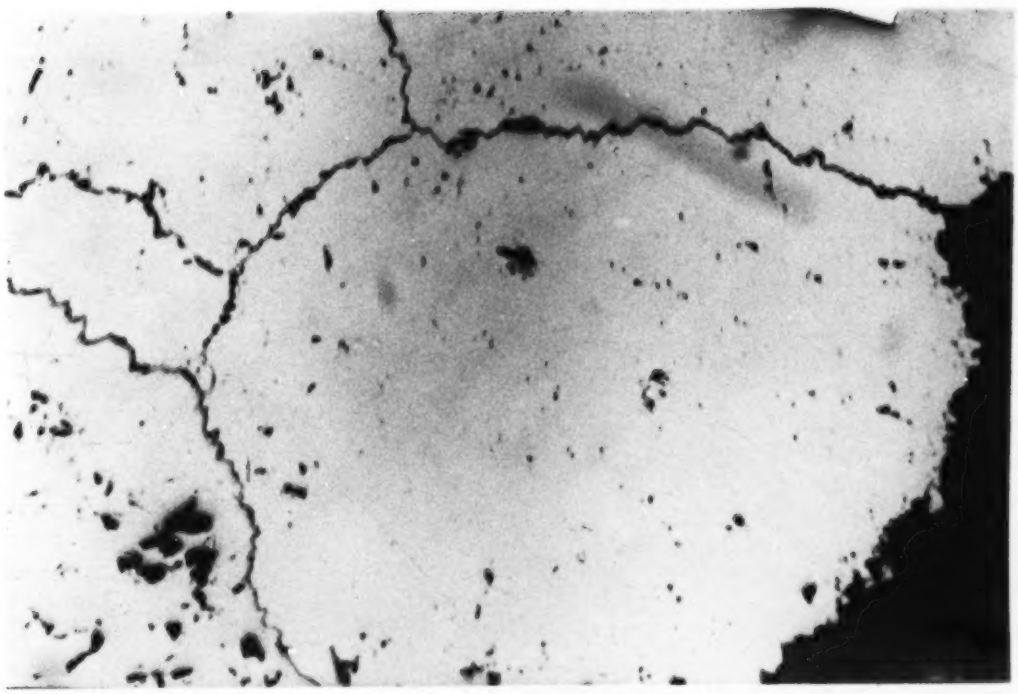


Figure 4.5.XX (C2/6). Polished mount under reflected light microscope. The interlocking boundaries between individual colloform masses are the result of recrystallization.
Scale: 1cm = 0.25mm

Recrystallization increases the grain size and removes impurities out of the system. Some of the banding of colloform sphalerite could originate from such outward moving impurity fronts of recrystallization. This cleaning process would also explain galena crystals growing on top of colloform sphalerite masses. Often these galena crystals are deeply rooted in the colloform sphalerite which could be the supplier of galena. A study of polished mounts of colloform sphalerite under reflected light shows how galena is accumulated and removed during recrystallization. Galena forms minute dendrites, perpendicular to the colloform banding of the sphalerite (Stage I, Fig.4.5.XXI). The formation of dendrites by disseminated crystals of galena during recrystallization reduces the energy level of the system. As the galena crystals move further out of the sphalerite, the dendrites introduce energy reduction by combining and infilling of the spaces between branches to form patches of galena (Stage II, Fig.4.5.XXII). On the surface of the colloform sphalerite, aggregates of the expelled galena accumulate, which increase in crystal size as they are further recrystallized (Stage III, Fig.4.5.XXIIV).

Figure 4.5.XXI (Sample C2/12). Polished mount. Minute galena dendrites in colloform sphalerite. Stage I of galena removal through recrystallization.
Scale: 1cm = 0.25mm

Figure 4.5.XXII (Sample C2/16). Patches of galena accumulating within colloform sphalerite. Stage II of galena removal through recrystallization.
Scale: 1cm = 0.1mm

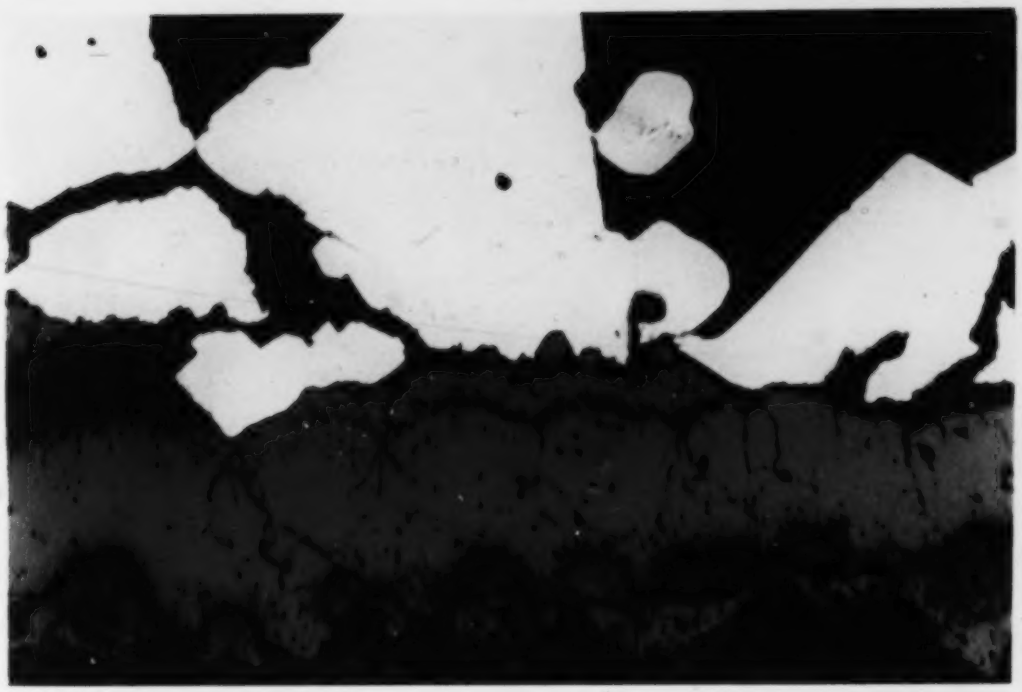


Figure 4.5.XXIIV (Sample C2/17). Galena crystals rooted in colloform sphalerite. Stage III of galena removal by recrystallization. Scale: 1cm = 0.25mm

Another sphalerite texture is also comprised of microcrystalline sulphides and is common in the main collapse zone of the K-77 ore body. This texture is formed by irregular bands of microcrystalline sphalerite which are 0.2 to 1.0 cm thick. Between the sphalerite bands are spaces which were infilled with sparite, less commonly with galena, or were left open. The often bulbous appearance of sequences of these bands has given rise to the theory that this texture originates from the replacement of organic

structures. It was found by the author that this lumpy line texture also occurs in banded structures that are difficult to relate to organisms: The texture occurs most commonly where ore concentration and recrystallization were highest and associated with inter-fragmental fill rather than the breccia fragments. This mode of occurrence makes the survival of organic textures unlikely and precipitation, growth and recrystallization have to be responsible for this lumpy line texture. In thin-section it can be recognized that the sphalerite bands are made up of spherical particles. The particles are consistently approximately 0.2 mm in diameter and well rounded. They are comprised of smaller crystals approximately 0.1 - 0.05 mm in diameter. There is no evidence for mechanical transportation. It appears that the spherical particles formed by the following process: They originated by the nucleation of sphalerite seeds in a supersaturated solution. The rapidly nucleating sphalerite seeds are virtually weightless and combine in suspension into rounded aggregates without anisotropic or directional growth. When the weight and radius (Stokes' Law) of the aggregate became sufficient, it settled, and with other aggregates, formed a layer of sphericules on a surface. During recrystallization the sphericules were transformed into crystalline framboidal sphalerite which are the round sphalerite particles observed in thin-section. The sphalerite bands consist of many of the sphalerite

framboids, which causes the lumpy shape of the bands. Compaction of the bands has caused pressure solution boundaries and fracturing. Recrystallization of the bands with its removal of inter- and intra- particle impurities and an increase in crystal size, has caused a volume loss and numerous layers of framboidal sphalerite separated from each other. The open spaces between layers were left open, or infilled with galena or sparite to produce the typical appearance of the lumpy line texture.

Figure 4.5.XXIV. Handspecimen. The "lumpy line" texture of sphalerite. Scale bar in cm.

Figure 4.5.XXV (C2/23). Thin section. The "lumpy line" texture of sphalerite. Scale: 1cm = 1mm

Massive layers of crystalline sphalerite or galena form other characteristic ore textures in this zone. It is very difficult to recognize any original sulfide textures since most of them have been overprinted by recrystallization.

After the initial mineralizing process, numerous mineralizing pulses filled cavities that were left open by previous acting solutions or by brecciation. Thick layers of sphalerite and galena were deposited during these pulses. The intense recrystallization of these layers makes it hard to differentiate between chemical or mechanical precipitation.

A common appearance of thick layers of sphalerite is the flame texture (Fig.4.5.XXVI). The flame like sphalerite crystals are up to 5 cm long and impinging and interlocking with neighboring crystals. In thin section, the outwardly directed crystals, their uniform colour and the crystal boundaries suggest outwardly moving fronts of recrystallization (Fig.4.5.XXVII). The primary sphalerite texture was probably of the rimming or capping type.

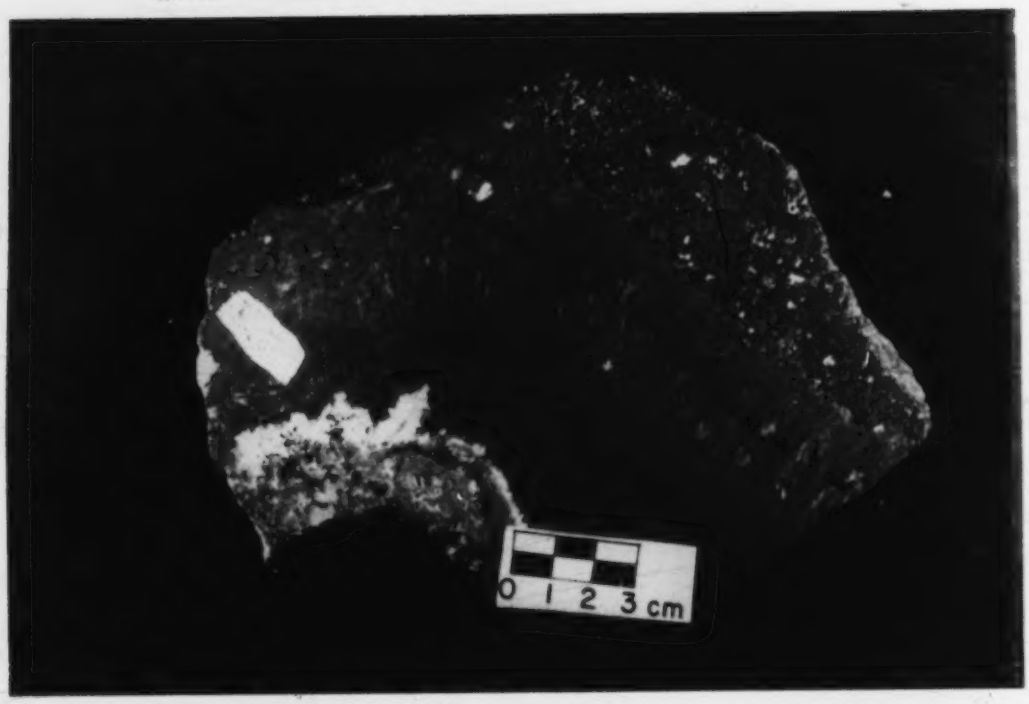


Figure 4.5.XXVI. Handspecimen. The "flame texture" of sphalerite.

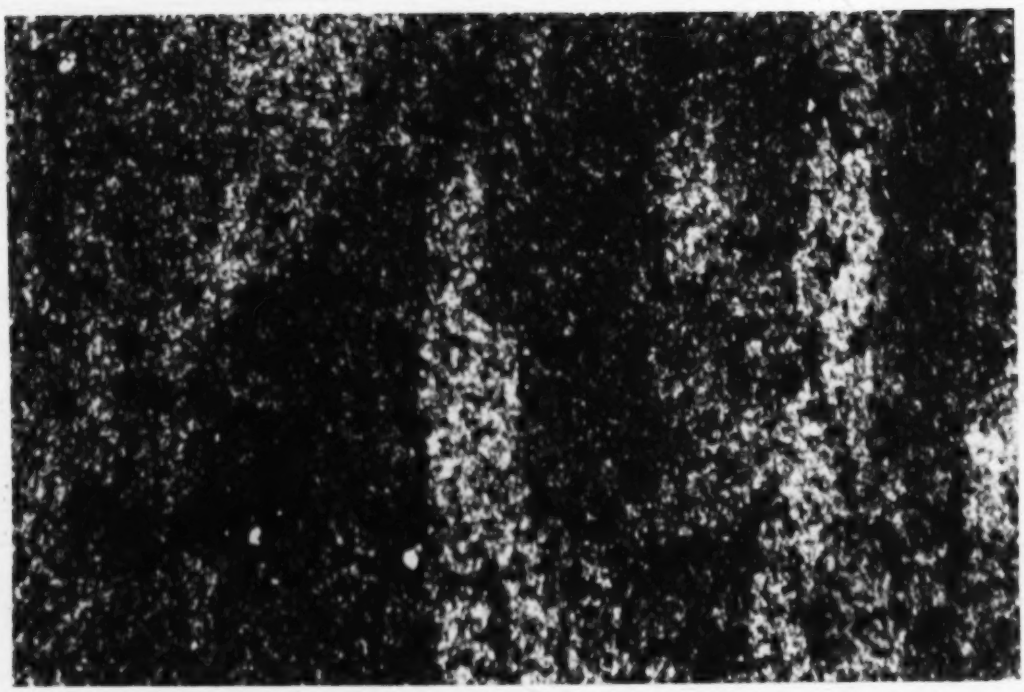


Figure 4.5.XXVII. Sphalerite "flame texture" in thin section. Scale: 1cm = 1mm

On the same handspecimen that shows the flame texture of sphalerite, a massive galena layer can be seen overlying the sphalerite (Fig.4.5.XXVI). In the K-77 ore body, the galena crystals of such massive layers commonly display a wormy texture. The wormy texture is the result of incomplete recrystallization of a previously formed layer of galena crystals. The way in which the galena initially accumulated is uncertain. It could have been detritally or chemically precipitated. Also possible is the concentration as a result of galena removal during sphalerite recrystallization. The galena layers consist of cm large skeletal, incomplete crystals. Interstitial sphalerite and carbonate, trapped within the crystal or between neighboring crystals prohibited the completion of the large galena crystals (Fig.4.5.XXIIX). Where galena is in the majority during recrystallization, the galena crystals will be wormy and sphalerite inclusions will be shard or lens shaped. With sphalerite in abundance over galena, sphalerite will form rounded masses if of colloform origin or large subhedral crystals with dendritic galena enclosed. These phase relationships have been previously discussed.

Figure 4.5.XXIIX. Polished mount showing "wormy galena"
Scale: 1cm = 0.1mm

The Mechanical Redistribution and Diagenesis of Ores

Sphalerite and galena were removed by solution currents from their original locations at open surfaces in cavities and fractures. Sphalerite especially (Fig.4.5.XXIX) shows rounding caused by abrasion in a traction current. Redeposited, the sphalerite grains form internal ore sediments. The pore-space of these sediments is either filled by cementation (e.g. sparite or crystal overgrowth) or reduced by compaction and pressure solution. Mechanically removed and transported galena behaves in a more brittle fashion and breaks into small pieces rather than becoming rounded (Fig.4.5.XXIX).

Transportation on small scale was observed in the cavities of wormy galena (Fig.4.5.XXIIX). After the incomplete recrystallization of the galena the interstitial sphalerite or carbonate was dissolved. Solutions that travelled through the newly created pore-space transported and redeposited fine grained particles.

Figure 4.5.XXIX (Sample 7/15). Thin-section of a fracture into which detrital galena and sphalerite were transported. Scale: 1cm = 0.5mm

Modern Ore Redistribution

Mineralization was not found in the K-77 sinter channel or in the sinkhole, as in the S-65 ore body. Therefore it is difficult to tie in ore redistribution with recent solution activities. However, lens shaped cavities in lateral extensions provide evidence of sphalerite growing out of solution at the present time. At these locations, sphalerite was found as crystalline coating on bulbous stalactites (Fig.4.5.XXX). This is certainly the most recent chemical precipitation of sphalerite.

Figure 4.5.XXX Outcrop of a recent sphalerite coated stalactites in lateral extension.

Ore Texture Logging of Diamond Drill Core of K-77

When it was recognized that certain ore textures correlate well with geological map units of ore bodies, diamond drill core was logged using these ore textures, to identify in this way the ore zones of various ore bodies. In the following, this procedure was applied to the K-77 ore body.

After relogging the complete core that had lead to the discovery and ore outline of K-77, a cross section was drawn through drill holes 24, 26, 15, 14 and 13 (Figure 4.5.XXXI). For comparison, this cross section was drawn at the same location as the initially prepared geological cross section (Figure 4.3.I). The characteristic ore textures used for the ore zone identification are listed in the legend of the cross section.

It was recognized that the peripheral zone is a transitional zone from unaltered limestone to the breccia zone. Laterally to the breccia zone, this peripheral zone is marked by the presence of marcasite in boxwork dolomite. Below the breccia zone the peripheral zone is a crackle breccia and only minute amounts of crystalline galena and sphalerite were found. The drill holes used for the construction of the cross section did not penetrate any marcasite zones at the bottom of the ore body.

On the cross-section the ore zone of intense recrystallization occurs:

- as an extension of the peripheral zone towards the breccia zone, or, related to the other ore zones in:
- internal sediments or
- the main ore zone.

In the latter two cases the white or blue-grey sparite with sphalerite stars overprints preexisting textures.

Internal sediments are often overlain by coarse grained sparite which is characteristic for intense recrystallization. The sparite with the sphalerite stars was primarily emplaced as open space fill. A common feature of the core were alternating horizons of internal sediment ore and recrystallization ore.

Internal sedimentation, characterized by the large euhedral galena crystals, occur laterally, below and within the main ore zone.

The ore textures of the main ore zone are greatly varied as previously mentioned. Interestingly, there is an increase of galena towards the top of the ore zone. The massive galena occurs in wormy textures which consist of cm large, incomplete crystals. The 25 cm (maximum) thick layers of galena are in a zone of approximately 10 m vertical thickness. Below this zone the amount of sphalerite increases. Massive layers of colloform or mosaic sphalerite are common.

The ore zone widens to the north and south with

depth. A lateral, tabular karst channel, mineralized by colloform sphalerite and some disseminated galena and sphalerite crystals, extends beyond the southern boundary of the cross section.

The presence of lateral karst extensions, the dome like closing in of unaltered limestone at the top and the unaltered limestone a the bottom of the deposit suggest that the mineralizing solutions entered the breccia zone from the sides. The galena concentration at the present top of the deposit suggest that water entering from the top was involved in the process of ore precipitation.

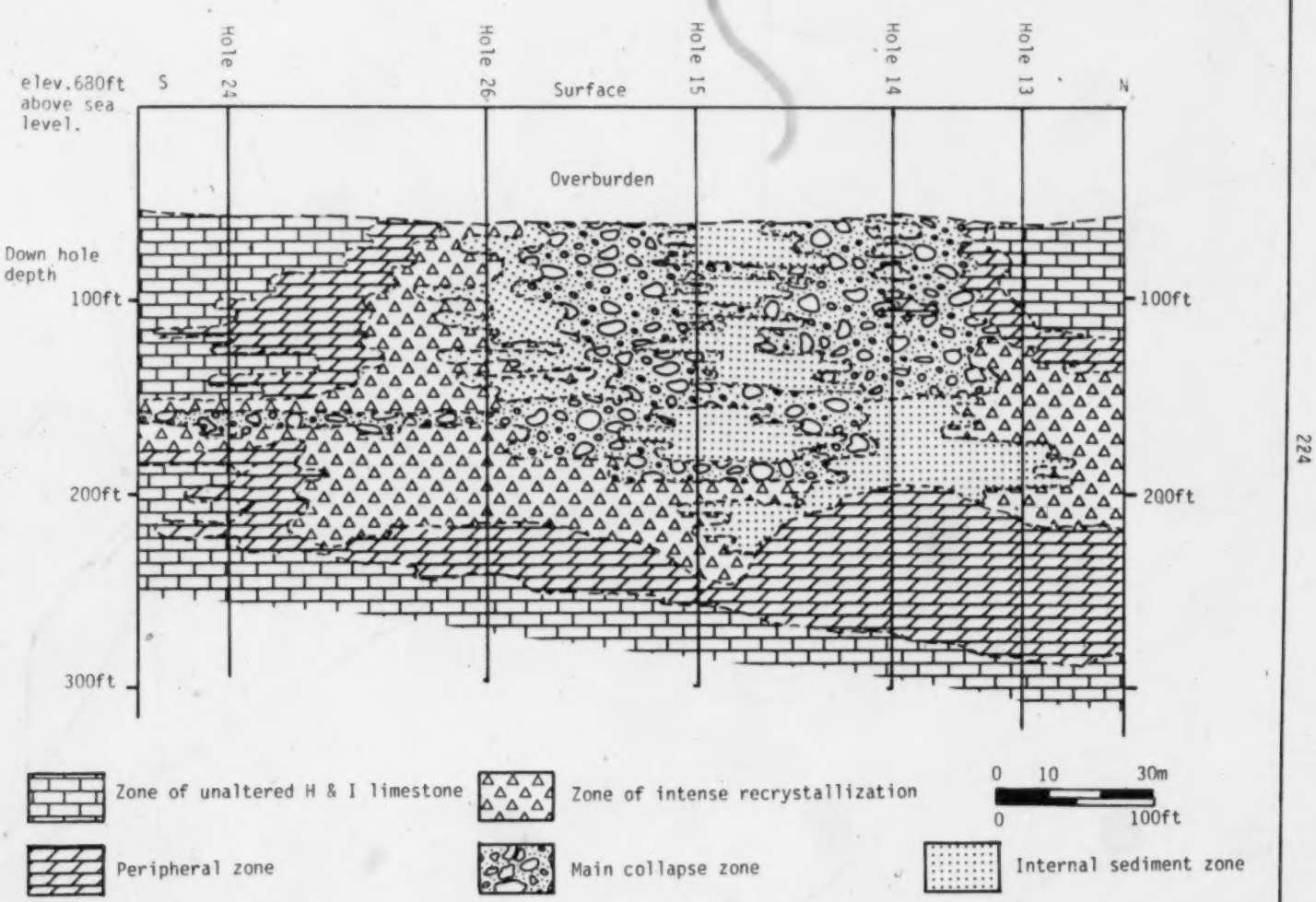


Figure 4.5.XXXI N - S Cross section showing the ore texture zonation through the K-77 ore body. (See Figure 4.4.I for the location of this section).

Listing of Ore Textures of K-77 and Summary

The following lists and summarizes the ore textures that were used to identify the host and ore zones of the cross section through K-77 (Figure 4.5.XXXII). The cross section was the result of host and ore mapping, ore texture mapping and relogging of the drill core:

- Unaltered H and I limestone
- Peripheral zone laterally of the ore body:
  - -patches and stringers of marcasite in boxwork dolomite
  - -massive marcasite
- Peripheral zone below the ore body:
  - -disseminated small, euhedral galena and sphalerite as fracture fill in crackle breccia
- Zone of intense recrystallization:
  - -rimming and capping sphalerite layers associated with blue-grey sparite
  - -sphalerite stars
  - -disseminated often dendritic aggregates of galena or sphalerite
  - -coarsening of all textures
  - -twinning

- Zone of internal sedimentation:
  - -Large galena cubes on top of the sediments
  - -Patchy disseminated often dendritic aggregates of sphalerite within the sediment
  - -Synsedimentary, disseminated galena cubes with secondary galena overgrowth
- Main ore zone:
  - -Colloform layers of sphalerite
  - -Wormy, massive galena
  - -Crystalline, mosaic sphalerite and sphalerite flame texture
  - -Lumpy line texture

The described textures are the result of chemical deposition and growth, detrital deposition and growth, authigenic nucleation and growth, and recrystallization.

Recrystallization was recognized to be a major ore texture forming process present in all ore zones. In the process of recrystallization crystals are "cleaned", continuously releasing amongst other impurites also hydrocarbons to the solutions. These hydrocarbons can facilitate the precipitation of the sulfides out of

solution. Precipitation of marcasite, sphalerite and galena appears to have occurred from the initial karsting to the present. In the same way, recrystallization of primary or secondary sulfide ore leads to the rejection of minor phases which eventually form coarse single phase layers. Bands of coarse galena crystals in colloform sphalerite represent such coarse single phase layers.

4.6. The K-77 Metal and Metal Ratio Distribution Maps

The Pb%+Zn% Distribution Maps

The combined lead and zinc sulfide map shows the distribution of minable sulfide ore. As in the case of the S-65 distribution maps, the 1.0%, 5.0% and 10.0% contour lines clearly delineate the trends within the ore body.

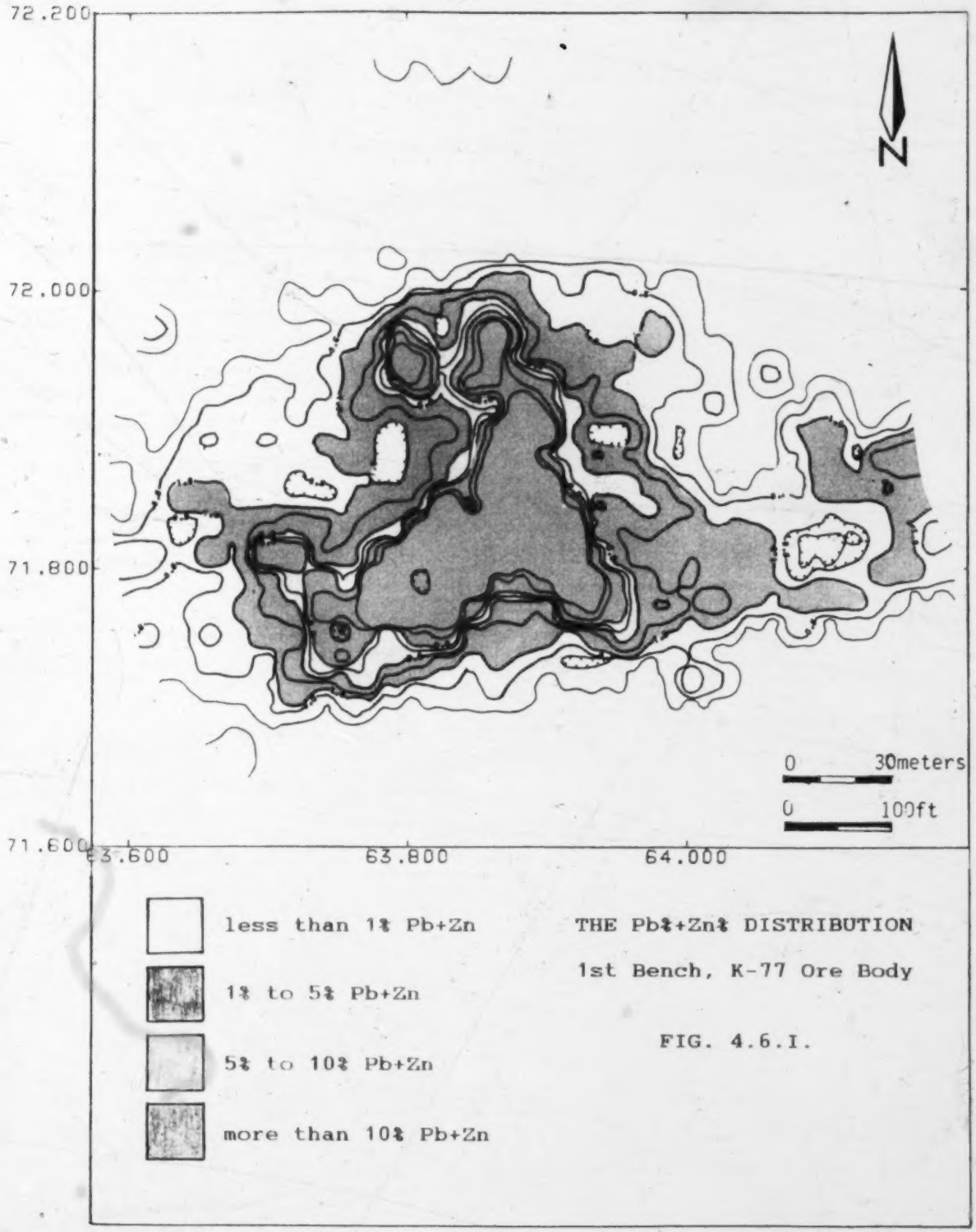
Unfortunately only diamond drill holes can be used to show the 3-dimensional shape of the ore body as mining and metal distribution contouring of the K-77 pit did not extend beyond the first bench.

On the first bench of K-77 the 1.0% Pb+Zn contour lines display the east-west elongation of the ore body, laterally extending into the pit walls. The ore body widens in a north-south direction in the centre of the pit. The width of the combined ore zone larger than 1.0% in the centre is approximately 100 m. While the 1.0% contour line in the south is relatively straight, the ore body is mostly protruding to the north. In the east and west lateral extensions of the ore body, most obvious in the east, are islands void of mineralization. This difference between east and west lateral extensions should give information about where solutions entered and exited.

The geology of the first bench shows that carbonates were replaced and recrystallized in the eastern lateral extension. However, sulfides were not deposited.

The author concluded from the above observations, that sulfides precipitated out of solutions which entered from the west. Solution activity began with the initial opening of karst channels which possibly occurred during the Mid-Givetian (Rhodes et al., 1984). The precipitation was facilitated by the hydrocarbons released during the process of recrystallization. As sulfide precipitation proceeded, the solutions were depleted of metals. By the time the solutions reached the exit-channels at the east side of the collapse zone, no further sulfide precipitation occurred from the depleted solutions.

The northern portion of the high grade combined ore (larger than 10% Pb+Zn) appears to be separated from the southern portion. This separation is caused by an east-west trending belt of low grade internal sediments.



THE Pb%+Zn% DISTRIBUTION

1st Bench, K-77 Ore Body

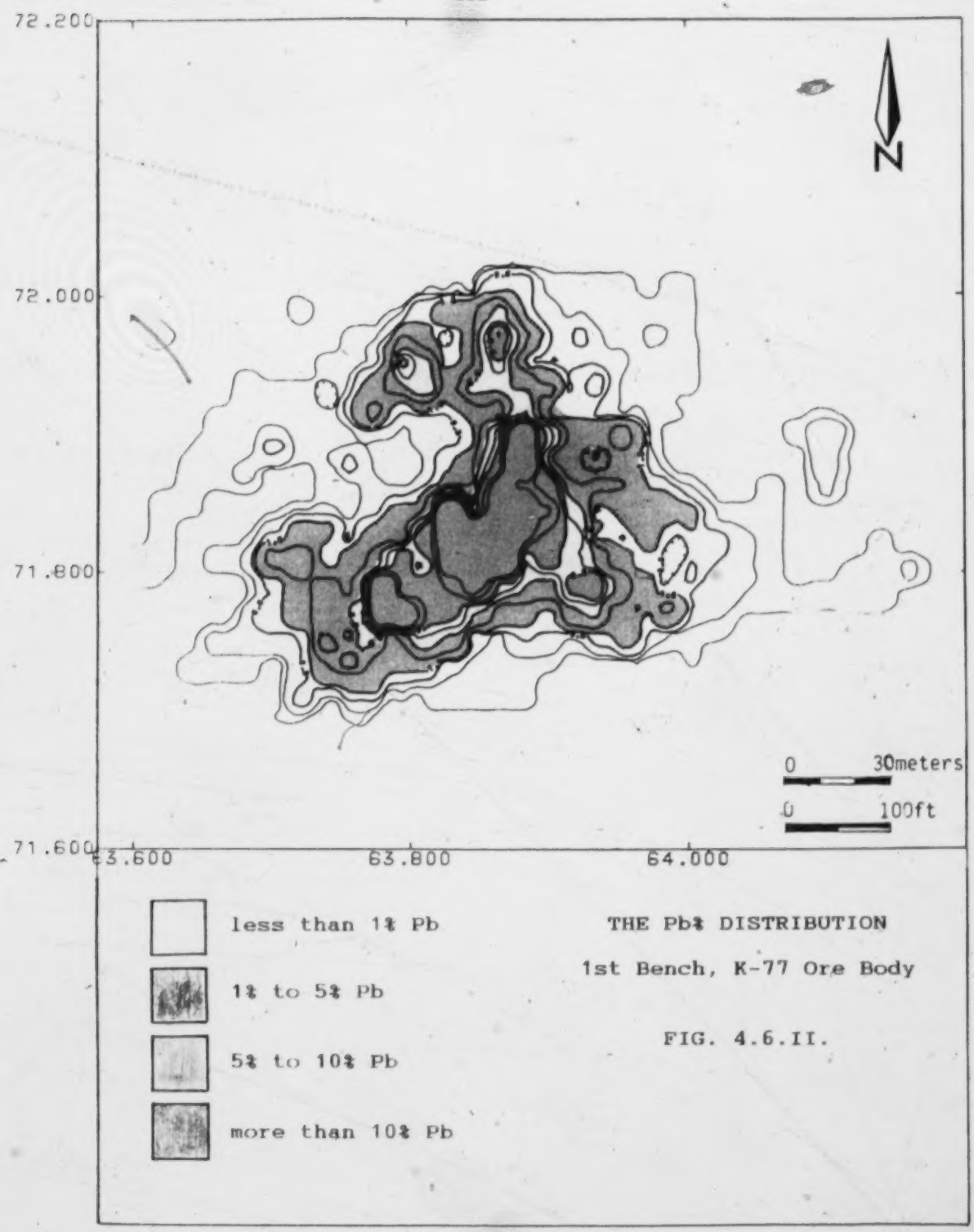
FIG. 4.6.I.

The Pb% Distribution Map

The difference between the location of galena and sphalerite crystallization became obvious in the separate Pb% and Zn% plots. It is obvious that the Pb ore formed the core of the combined ore.

The lead values increase inwardly from the edge of the ore body at a constant rate (constant contour spacing) until approximately 5% Pb is reached. Then the values jump to over 10% to form the single, high grade lead core of the ore body. This constant trend and high grade core can be readily recognized on the Pb%/Zn% distribution map.

The east-west lateral extensions can be recognized on the Pb% distribution map. The north extension is poorly outlined. Because lead is less mobile than zinc or iron, the lead distribution map shows the outline of primary ore deposition along the east - west trending solution zone. Later secondary ore redistribution involving the north lateral extensions had little impact on the lead distribution.



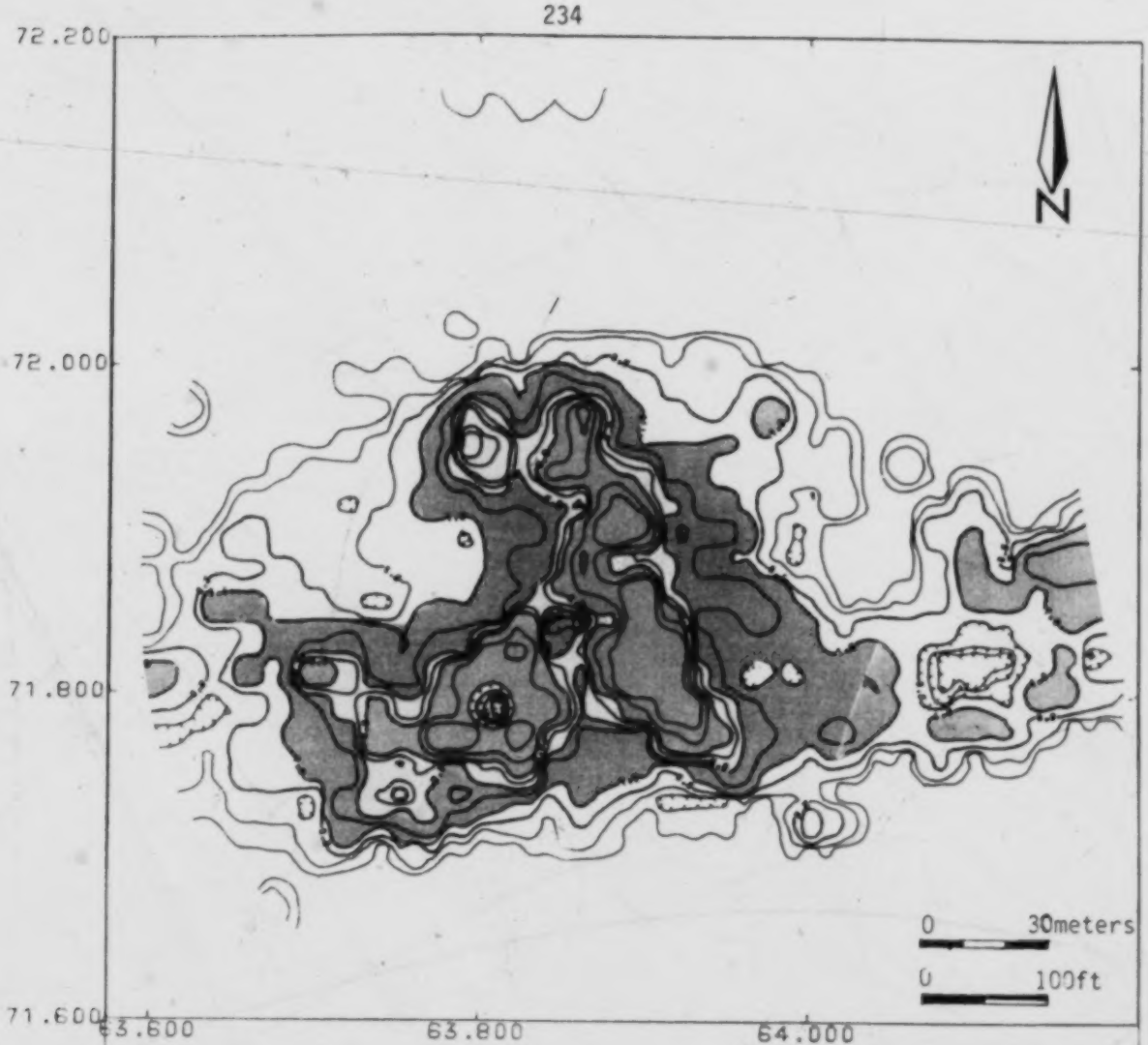
THE Pb% DISTRIBUTION

1st Bench, K-77 Ore Body

FIG. 4.6.II.

The Zn% Distribution Map

The Zn% reaches generally the same high as the Pb% (15-20%) but covers a larger area. Especially the area outlined by 0.5% and 1.0% contour lines is considerably larger. It is noticeable that the contour spacing from low Zn% to high grade is constant, indicating a more gradual increase in values than the Pb% concentrations. The explanation of the difference in gradients in Pb% and Zn% distribution is the difference in energies involved to start galena and sphalerite crystals. The concentration level of the solutions has to reach a peak to start galena seed-crystals. Galena crystals then grow incompletely and rapidly to quickly lower the concentration level. However, sphalerite crystals can grow on marcasite seeds. Therefore, sphalerite grows more steadily at lower energy levels and it rarely comes to excessive precipitation of sphalerite. The greater mobility of zinc subjects sphalerite more than galena to the processes of redistribution by solutions after primary deposition. Sphalerite is, therefore, not as restricted to the high grade core of the deposit and is present in almost all lateral solution channels.



less than 1% Zn

1% to 5% Zn

5% to 10% Zn

more than 10% Zn

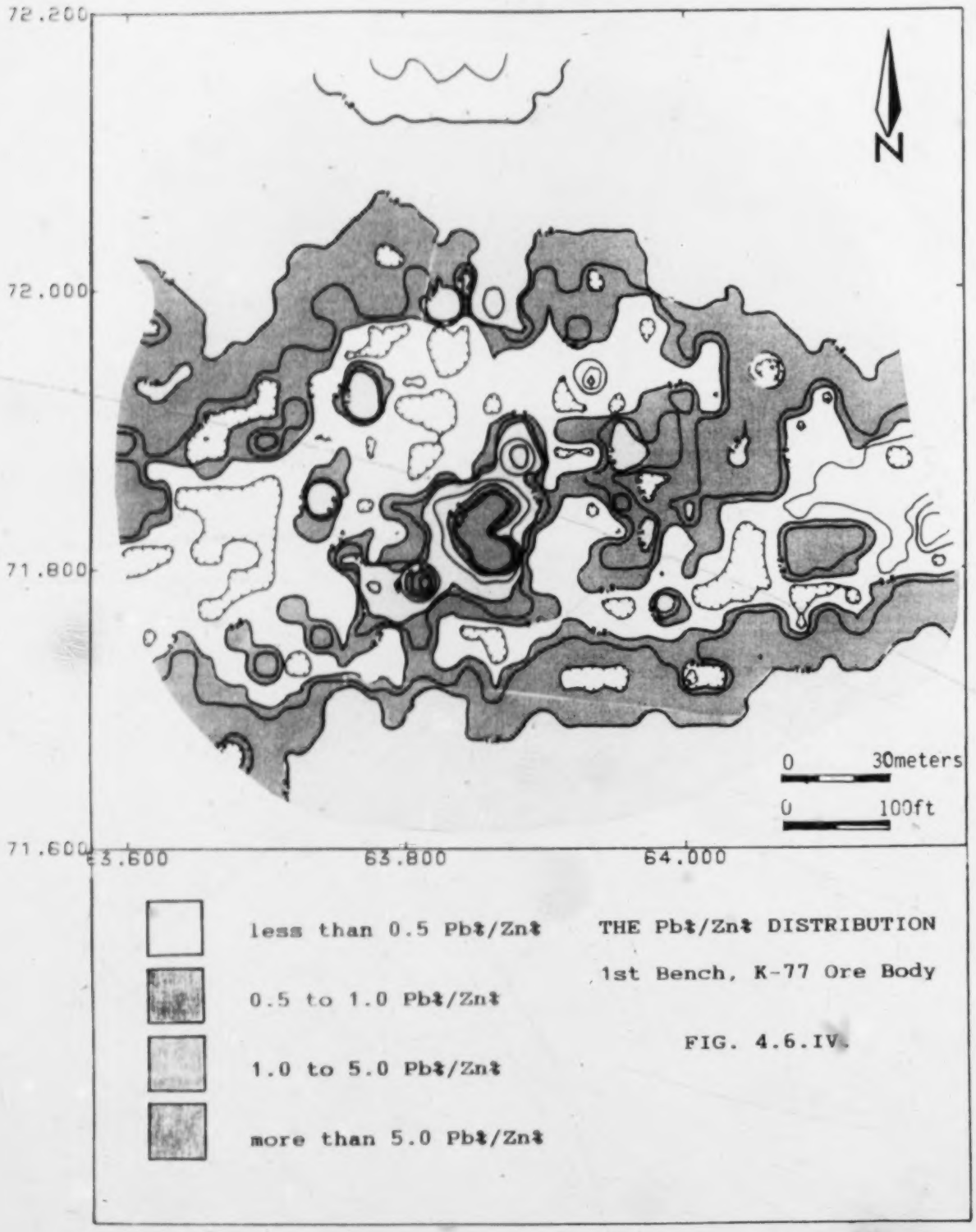
THE Zn% DISTRIBUTION

1st Bench, K-77 Ore Body

FIG. 4.6.III.

The Pb%/Zn% Distribution Map

The observations made on the separate Pb% and Zn% maps are emphasized on the Pb%/Zn% distribution map. The relative Zn% high (white and blue) outlines the east-west trending solution channel. The eastern lateral extension is narrower and has slightly lower relative Zn% values than the western extension. The core of the ore body has a strong, (broken up into two larger than 5.0 Pb% zones) relative Pb%/Zn% high. This high coincides with the breccia zone of the ore body.



THE Pb%/Zn% DISTRIBUTION

1st Bench, K-77 Ore Body

FIG. 4.6.IV.

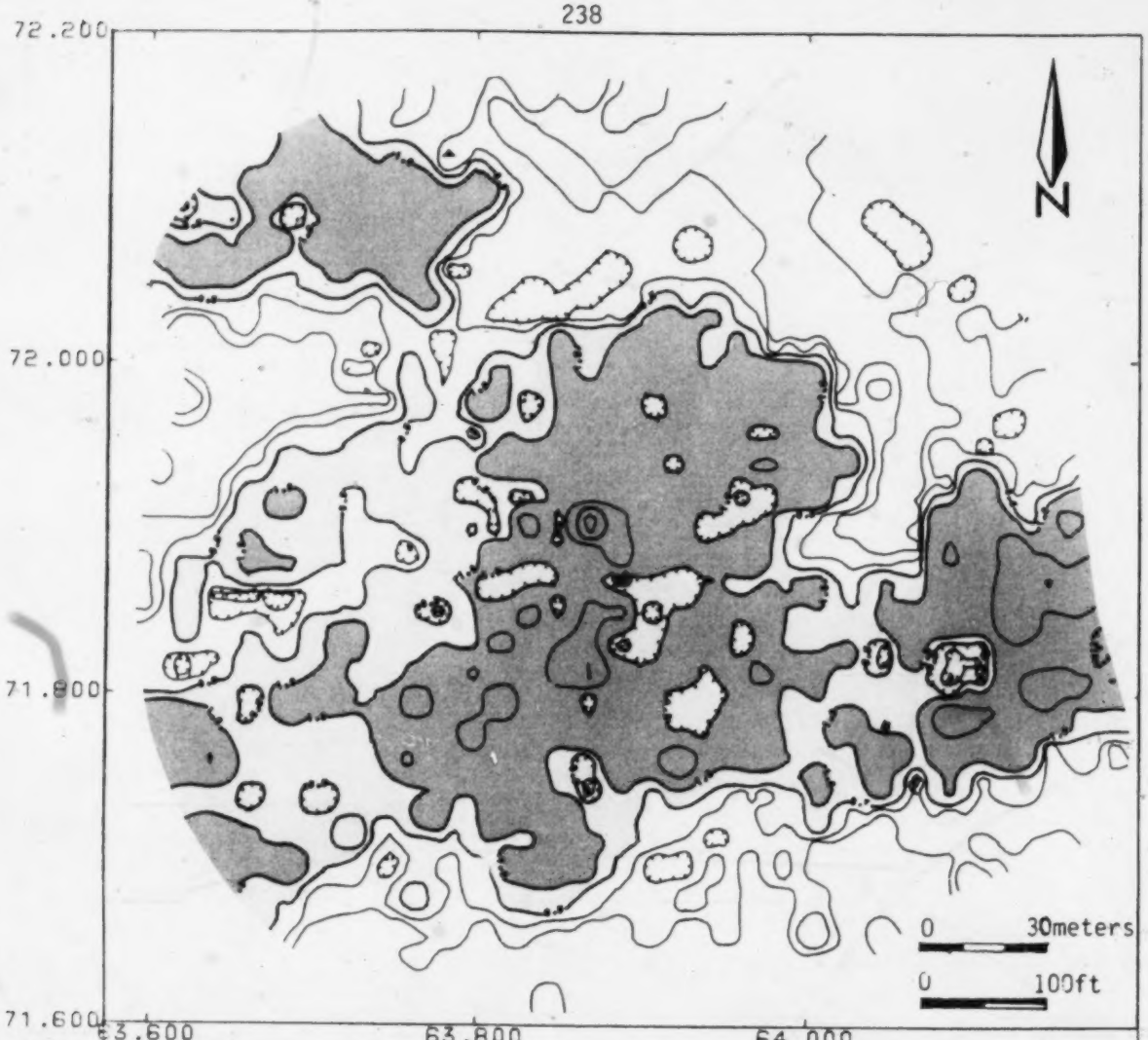
The Fe% Distribution Map

The area outlined with the 0.5 and 1.0% contour lines covers the east-west trending of the ore body without highlighting any detail.

In general an increase of Fe% towards the eastern lateral extension can be observed.

Different from any other Distribution map is the iron concentration towards the north-west of the ore body. This increase in marcasite clearly coincides with the location of the Pleistocene Sinkhole. No economic mineralization is associated with this sinkhole.

The marcasite seems to occur in any previously formed solution channels and deposited later and separately from galena and sphalerite.



less than 0.5% Fe

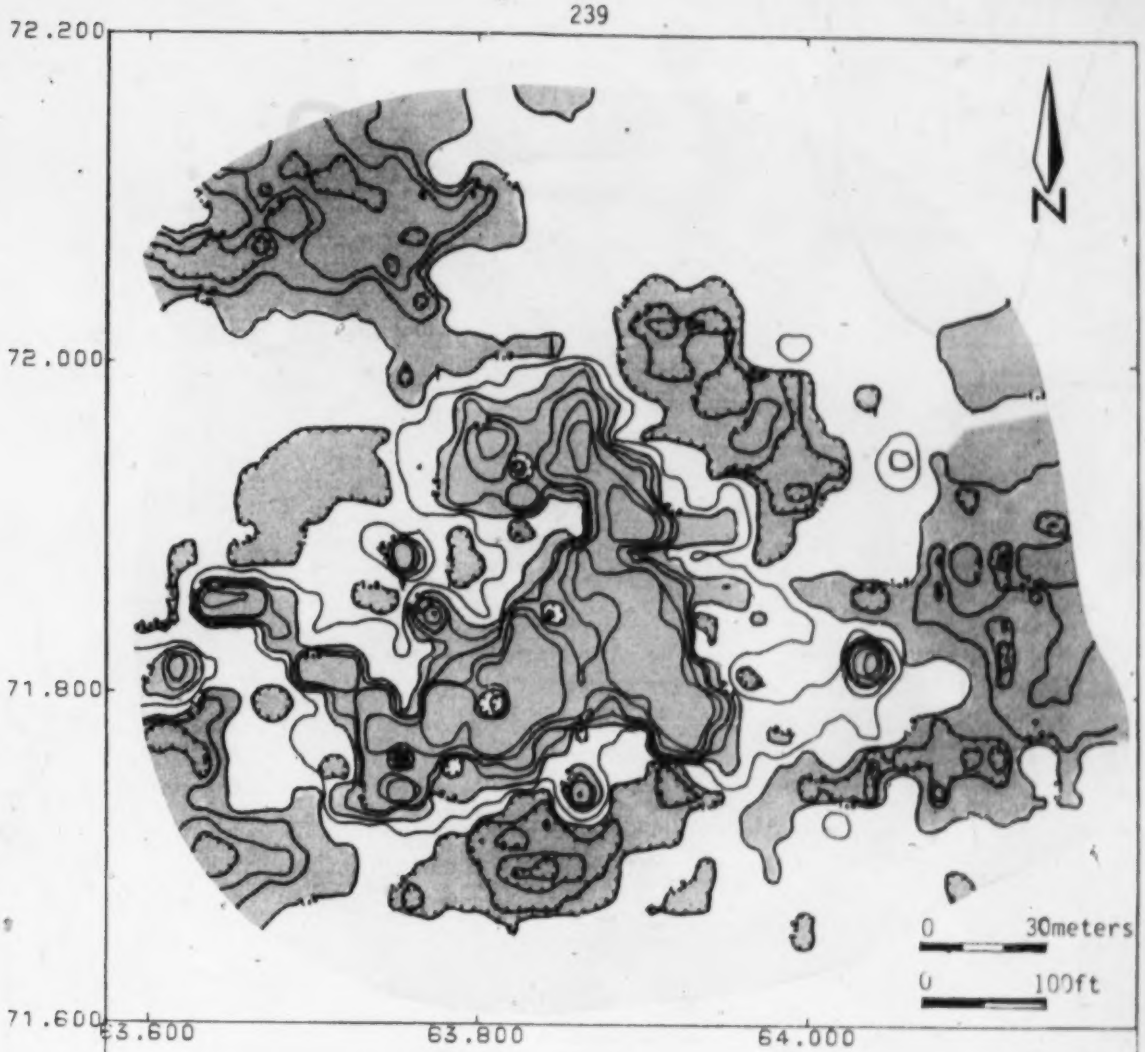
0.5% to 1.0% Fe

more than 1.0% Fe

THE Fe% DISTRIBUTION

1st Bench, K-77 Ore Body

FIG. 4.6.V.



0.5 to 1.0 $\frac{Pb\%+Zn\%}{Fe\%}$

1.0 to 5.0 $\frac{Pb\%+Zn\%}{Fe\%}$

5.0 to 10.0 $\frac{Pb\%+Zn\%}{Fe\%}$

more than 10.0 $\frac{Pb\%+Zn\%}{Fe\%}$

THE $\frac{Pb\%+Zn\%}{Fe\%}$ DISTRIBUTION

1st Bench, K-77 Ore Body

Fig. 4.6.VI.

4.8 CONCLUSIONS AND DISCUSSIONS

Conclusion and Discussion of the General and Host Rock Geology of K-77

K-77 is a prismatic ore body in the west part of the Main Trend, and occurs in the H and I-facies of the Sulphur Point Formation. Proven reserves of the K-77 deposit were 647,700 tons at 3.9 % combined Pb+Zn. Diamond drilling at the K-77 location revealed an east-west trending solution zone with a paleo collapse zone as wide as 100 m. At the base of the karst formation the D3-horizon is thickened by what appears to be a depositional high. This depositional high probably enhanced karsting processes in overlying carbonates. Drilling and pit mapping revealed the following mappable geological zones:

The unaltered H and I-limestone host shows very little indication of the immediately adjacent ore deposit. Some fracturing and recrystallization indicates solution activity. A halo of Presqu'ile dolomite occurs around the ore body (Peripheral Zone). The boxwork texture and crackle brecciation show the closeness to the collapse zone. The central, high grade Main Collapse Zone has sharp boundaries. The open spaces facilitated the highest, ore forming solution activity and in multiple, unidentifiable stages deposited, dissolved and redistributed the ore. The internal sediments to the north, west and south of the main collapse

are evidence of such redistribution processes. Marcasite enrichment to the south and east of the main collapse is commonly associated with internal sediments but was brought in by later solution activity. Intense recrystallization along the south and east of the collapse zone is the result of continueous solution activity after the initial karst formation. Modern karst activities are reflected by sinter zones and a sinkhole.

Conclusion and Discussion of the Ore Texture Zones of K-77

In the process of ore texture mapping of the first bench of K-77 and the ore texture logging of drill core four texture zones were identified:

The peripheral zone
The internal sediment zone
The recrystallization zone
The collapse zone

A complete listing of the ore textures found in each zone is presented at the end of chapter 4.5. There are a few typical ore textures which allow a quick identification of the ore zone. Such textures are usefull during grade control or core logging.

The peripheral zone is readily identified by the boxwork texture. Late marcasite often accumulates along fractures and is followed by occasional sphalerite. Groups of euhedral galena crystals characterize the internal sediment zone. Sphalerite occurs in patches of disseminated crystals. In the zone of intense recrystallization blue-grey and white sparite are a common host. Very common are coarse crystalline galena dendrites and sphalerite stars. The overwhelming amount of repeated cross-cutting textural relationships in the main ore zone make it impossible to assign certain textures to certain stages of mineralization. Stages can only be followed on a local scale of meters, beyond which they are again overprinted. The sulfides occur in the following settings:

- Rimming and cementing breccia fragments
- Filling large primary or secondary open spaces
- Associated with recrystallization
- Associated with internal sedimentation

When it was recognized that certain ore textures correlate with geological map units of ore bodies, a cross section of the entire K-77 ore body was prepared from recorded textures of pit samples and drill core (Figure 4.6.I).

The ore texture and host rock mapping shows that the ore zone widens to the north and south with depth. A

lateral, tabular karst channel, mineralized by colloform sphalerite and some disseminated galena and sphalerite crystals, extends beyond the southern boundary of the cross section.

The presence of lateral karst extensions, the dome like closing in of unaltered limestone at the top and the unaltered limestone a the bottom of the deposit suggest that the mineralizing solutions entered the breccia zone from the sides. The galena concentration at the present top of the deposit suggest that water entering from the top was involved in the process of ore precipitation.

Conclusion and Discussion of the K-77 Metal and Metal Ratio Distribution Maps

The Pb% + Zn% distribution map delineates the general trends within the ore body. It reveals an east - west elongation with lateral extensions on the east and west sides of the central high grade zone. It appears that the main flow direction of sulfide precipitating solutions was from the west to the east. There is an indication for a lateral extension to the north, however, it is overprinted by a Pleistocene sinkhole. Internal sediments separate the northern part of the high grade ore from the southern portion.

The Pb% distribution is as in the S-65 orebody more confined to the core of the central high grade zone and shows the northern lateral extension less clearly. Because lead is less mobile than zinc or iron, the lead distribution map shows the outline of primary ore deposition along the east - west trending solution zone. Later secondary ore redistribution involving the north lateral extensions had little impact on the lead distribution.

The greater mobility of zinc subjects sphalerite more than galena to the processes of redistribution by solutions after primary deposition. Sphalerite is, therefore, not as restricted to the high grade core of the deposit and is present in almost all lateral solution channels which can be seen on the Zn% distribution maps.

The Pb%/Zn% distribution maps combine the above observations by displaying the high grade core (high Pb%) and the east, west and north solution channels.

Different from any other distribution map is the iron concentration towards the north-west of the ore body at the location of the Pleistocene Sinkhole. No economic mineralization is associated with this sinkhole. The marcasite occurs in previously formed solution channels and deposited later and separately from galena and sphalerite.

Correlation of Grade Contours with Texture Zones of K-77

The lead + zinc over iron ratio map (Fig.4.6.VI) provides a combination of the previously described maps.

The areas of 0.5 to 1.0 (Pb%+Zn%)/Fe% typically fall into the Peripheral Zone representing a marcasite rim around the central ore zones. The higher than 5.0 (Pb%+Zn%)/Fe are concentrated in the Breccia or Main Ore Zone.

The ore texture zones outlined on Figure 4.4.I were superimposed on the (Pb%+Zn%)/Fe% distribution map, yielding typical ore grades for the individual ore texture zones. The area calculations were performed using a planimeter and are, therefore, approximations. The ranges of grades within contour intervals were averaged for the purpose of this calculation. The resulting average grades within the individual texture zones were as follows:

Peripheral Zone

0.5 - 1.0 (avg.0.75)	(Pb%+Zn%)/Fe%	1,457 m^2
1.0 - 5.0 (avg.3.0)	(Pb%+Zn%)/Fe%	3,206 m^2
more than 5.0 (avg.7.5)	(Pb%+Zn%)/Fe	135 m^2
Total combined area of peripheral zones:		4,799 m^2

Total grade average: 2.44 (Pb%+Zn%)/Fe%

Zone of Intense Recrystallization

0.5 - 1.0 (avg.0.75)	(Pb%+Zn%)/Fe%	163 m^2
1.0 - 5.0 (avg.3.0)	(Pb%+Zn%)/Fe%	317 m^2
more than 5.0 (avg.7.5)	(Pb%+Zn%)/Fe%	136 m^2
Total combined area of intense recrystallization zones:		616 m^2

Total grade average: 3.4 (Pb%+Zn%)/Fe%

Zone of Internal Sediments

0.5 - 1.0 (avg.0.75)	(Pb%+Zn%)/Fe%	90 m^2
1.0 - 5.0 (avg.3.0)	(Pb%+Zn%)/Fe%	905 m^2
more than 5.0 (avg.7.5)	(Pb%+Zn%)/Fe%	742 m^2
Total combined area of int. sediment zones:		1,793 m^2

Total grade average: 4.6 (Pb%+Zn%)/Fe%

Breccia Zone:

1.0 - 5.0 (avg.3.0)	(Pb%+Zn%)/Fe%	362 m^2
more than 5.0 (avg.7.5)	(Pb%+Zn%)/Fe%	1,123 m^2
Total combined area of breccia zones:		1,485 m^2

Total grade average: 6.4 (Pb%+Zn%)/Fe%

The average (Pb%+Zn%)/Fe values for the individual zone increase gradually from the outside to the center of the ore body. The lowest values are in the Peripheral Zone where lead / zinc mineralization is rare and marcasite

occurs frequently in fractures and cavities. The highest values of the combined ore over iron ratio occur in the central, brecciated ore zone. The zones of recrystallization and internal sedimentation occur at the approximate same distance and orientation to the central zone. However their respective combined ore over iron ratios differ substantially. This difference is caused by the following processes: In the zone of recrystallization, with an average ratio of 3.4, there was no redistribution of galena, sphalerite or marcasite with the exception of minor, small scale mobilization associated with the recrystallization. This has kept the ore grades constant since the initial formation of the ore deposit. In the Zone of Internal Sedimentation, with an average ratio of 4.6, material was initially removed to create caves. These caves were subsequently infilled with internal sediments which were in the case of the K-77 deposit derived from the high grade breccia zone.

5. DISCUSSION AND CONCLUSION OF THE GEOLOGY, ORE TEXTURES AND METAL DISTRIBUTIONS OF THE S-65 AND K-77 ORE BODIES.

The textures within the ore bodies allow a differentiation into the peripheral, marcasite rich, internal sediment, and the main collapse ore textural zones. A major texture forming process in all the zones, however, was the overprinting and redistributing processes of recrystallization.

The metal distribution maps reveal distinct characteristics for the sphalerite, galena and iron distribution. The three metals and their plotted ratios, allow the recognition of the primary ore deposition, repeated and continuous redistribution, and the redistribution up to the present. The redistribution involved a solution and material flow from the lateral extensions of the breccia zones as well as from the openings at the top at different stages.

The observations made on the processes of recrystallization offer new approaches for the genesis and paragenesis of the Pine Point, Mississippi Valley Type ores. The first karsting processes (Middle Givetian) connected pores and fractures to a channel system. Where the channels crossed, cavities, stoping and brecciation occurred.

Subsequently the caves and breccia zones increased in size. The open spaces enhanced recrystallization, as it allowed carbonate crystals to shift, grow and remove impurities as part of the recrystallization process. Recrystallization has been a continuous process ever since the initial karsting. The removal of impurities during recrystallization continuously released H_2S into karst openings.

The availability of sulfur is important in determining whether a sedimentary brine can be an ore forming solution. In the early diagenesis of a carbonate sediment, bacteria reduced dissolved sulfur in the interstitial sediment water to iron sulfides and H_2S. The resulting sulfides and sulfide rich brines were necessary for the precipitation and remobilization of galena and sphalerite.

The ore forming solution carried a certain amount of lead and zinc. However, since the sulfides which triggered the precipitation of sphalerite and galena were released continuously (since the Givetian), very low, constant metal concentrations of the brine were required to form the deposits over such a long time period. Roedder (1960) calculated that a brine containing only 1 ppm of a metal can form an ore deposit in 10^5 years. This makes a major metal supplying event unnecessary. The McDonald Fault

and the Athapuskow Aulacogen likely played a passive role in the location of the reef complex. However, there is insufficient tectonic evidence in or near the deposits to support exhalative or igneous activities in the vicinity, and/or as metal supplier to the Pine Point deposits.

Standard brines with slightly elevated metal concentrations provided the metals which were deposited in the Pine Point karst system. Sphalerite, galena and marcasite precipitation was triggered by sulfides which were and are continuously released by recrystallization and other diagenetic processes. It appears that, over time, the metal content of the brines has gradually decreased. In recent time redistribution of ore is more prominent than any new ore deposition.

When studying hundreds of samples from many different locations in the Pine Point district, it became apparent that one cannot differentiate on a deposit or district scale between distinct stages or phases of any of carbonate precipitation, carbonate removal, sulphide deposition, sulfide dissolution and redistribution. Many genetic or paragenetic diagrams presented for the Pine Point deposits were produced by most of the previous authors from a small number of samples and are only valid within a few meters from where the samples were taken.

The metal distribution maps shed additional light on the processes of precipitation and redistribution of the sulfides. Lead appears to be concentrated in the central breccia zone. Lead is not significantly affected by processes of redistribution, because lead does not dissolve or precipitate easily. High energy levels were required to seed new galena crystals, and the specific gravity of galena limited detrital redistribution. Zinc dissolved more easily and required lower energy levels to nucleate than galena. An additional factor which enhanced the redistribution of sphalerite was that new sphalerite crystals can start on a marcasite base. The surface energy of marcasite reduces the energy threshold of such sphalerite crystal nucleation. Also, sphalerite has a lesser specific gravity than galena and is readily transported by traction currents. Consequently the zinc distribution maps, in comparison with the lead maps, show the locations of solution activities in greater detail. Iron precipitated, redistributed, dissolved and was replaced most readily of the three metals studied. It grew in fresh fractures in yet unrecrystallized carbonates, further grew as recrystallization progressed, and provided surface energy for the nucleation of sphalerite. In general the iron contours extend well beyond the map limits of the pit walls limiting the use of the contour lines for interpretations of most solution activities. However, marcasite concentrations within the

limits of the pit outlined the most recent solution activity in the Pleistocene sink holes and recent sinter deposits.

Recrystallization is ubiquitous in the deposits. Texturally significant is the exsolution by recrystallization of sphalerite and galena. This is mostly visible in colloform aggregates of sphalerite, where small sphalerite grains combine into larger crystals, rejecting impurities like galena. The rejected galena accumulated as stringers and dendrites perpendicular to the sphalerite banding. With further recrystallization the galena stringers reached the surface of colloform sphalerite deposits where they accumulated as coarse crystals. Resulting alternating sulfide layers were in the past interpreted as a result of selective precipitation from solutions with changing metal content. According to this study, the such layers can also be the result of exsolution by recrystallization.

The studies in this thesis apply to the grade control routine in a mining operation (1) and provide new information for the genetic modelling of the Pine Point and other Mississippi Valley Type (MVT) deposits (2).

(1) The results support a relationship between ore textures and metal distribution. The characteristic ore grades for the individual ore textural zones vary between ore bodies. The regular investigation of textures,

therefore, would have limited usefulness for the grade control department of Pine Point Mines or other MVT mining operations.

(2) The study shows that ore deposition is associated with karsting and likely began in Mid-Givetian time. Deposition of "new" ore and redistribution of previously deposited ore has taken place continuously up to recent times.

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